CRANFIELD UNIVERSITY

WAN MOHD SUFIAN BIN WAN HUSAIN

MAINTAINABILITY PREDICTION FOR AIRCRAFT MECHANICAL COMPONENTS UTILISING AIRCRAFT FEEDBACK INFORMATION

SCHOOL OF ENGINEERING
Department Of Aerospace Engineering

Doctor of Philosophy
Academic Year: 2007 - 2011

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

The aim of this research is to propose an alternative approach to determine the maintainability prediction for aircraft components. In this research, the author looks at certain areas of the maintainability prediction process where missteps or misapplications most commonly occur. The first of these is during the early stage of the Design for Maintainability (DfMt) process. The author discovered the importance of utilising historical information or feedback information. The second area is during the maintainability prediction where the maintenance of components is quantified; here, the author proposes having the maximum target for each individual maintainability component.

This research attempts to utilise aircraft maintenance historical data and information (i.e. feedback information systems). Aircraft feedback information contains various types of information that could be used for future improvement rather than just the failure elements. Literature shows that feedback information such as Service Difficulty Reporting System (SDRS) and Air Accidents Investigation Branch, (AAIB) reports have helped to identify the critical and sensitive components that need more attention for further improvement.

This research consists of two elements. The first is to identity and analyse historical data. The second is to identify existing maintainability prediction methodologies and propose an improved methodology. The 10 years' data from Federal Aviation Administration (FAA) SDRS data of all aircraft were collected and analysed in accordance with the proposed methodology before the processes of maintainability allocation and prediction were carried out.

The maintainability was predicted to identify the potential task time for each individual aircraft component. The predicted tasks time in this research has to be in accordance with industrial real tasks time were possible. One of the identified solutions is by using maintainability allocation methodology. The existing maintainability allocation methodology was improved, tested, and validated by using several case studies. The outcomes were found to be very successful.

Overall, this research has proposed a new methodology for maintainability prediction by integrating two important elements: historical data information, and maintainability allocation. The study shows that the aircraft maintenance related feedback information systems analyses were very useful for deciding maintainability effectiveness; these include planning, organising maintenance and design improvement. There is no doubt that historical data information has the ability to contribute an important role in design activities. The results also show that maintainability is an importance measure that can be used as a guideline for managing efforts made for the improvement of aircraft components.

Keywords:

Aircraft Maintenance, Historical data, Maintainability allocation, Maintainability prediction

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PUBLICATIONS

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POSTERS

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NOMENCLATURE

λ	Failure Rate
λ_j	Failure Rate of each unit
λ_p	Failure Rate for total units
k	Weighting factor
AAIB	Air Accident Investigations Branch
AD	Airworthiness Directive
A_i	Inherent Availability
ASRS	Aviation Safety Reporting Systems
UK CAA	United Kingdom Civil Aviation Authority
CAAIP	Civil Aircraft Airworthiness Information and Procedures
DfA	Design for Assembly
DfD	Design for Disassembly
DfM	Design for Manufacturing
DfMt	Design for Maintainability
DfX	Design for "X"
DRACAS	Data Reporting, Analysis and Corrective Action Systems
EASA	European Aircraft Safety Agency
e_i	Absolute Error
f_i	The prediction value
FAA	Federal Aviation Administration
FRACAS	Failure Reporting, Analysis and Corrective Action Systems

FR	Refer λ
IATA	International Air Transport Association
JASC	Joint Aircraft System and Component
MAE	Mean Absolute Error
M_{ct}	Maintenance Corrective Time
MEDA	Maintenance Error Decision Aid
MEMS	Maintenance Error Management System
MRO	Maintenance Repair Organisation
MTBF	Mean Time to Failure
MTTR	Mean Time to Repair
PRACAS	Problem Reporting, Analysis and Corrective Action Systems
R & R	Remove and Replace
R_{pj}	Active Repair Time of each unit
R_{pp}	Active Repair Time of total units
SB	Service Bulletin
SDR	Service Difficulty Reports
SDRS	Service Difficulty Reporting System
SL	Service Letter
SR	Service Difficulty Rate
y_i	The true value

1 Introduction

The maintenance through prediction methodology has very often been seen as one of the potential areas where maintenance effectiveness targets can be easily and quickly achieved. They can be achieved through an understanding of historical information from previous designs and feedback information supplied by aircraft mechanics, engineers and/or aviation regulators. There are many types of aircraft related historical data available to be collected, compiled and analysed for future improvement. The idea is to ensure that occurrences do not happen again as well as to ensure the element of safety is improved. Failure rate (λ) is one piece of historical information and for many years failure rates (λ) were important elements used to predict maintainability effectiveness.

In this chapter, the purpose of the research is introduced regarding the background of maintainability, the importance of maintainability and to highlight the opportunities to improve the existing scenario such as the opportunities for closing the identified gaps and/or problems. This chapter covers the background and problem areas of the research project. It also discusses the research question's limitations and finally the structure of the thesis is specified.

1.1 Background

One of the value drivers in the civil aircraft industry is aircraft maintenance. Collectively it is defined as the time taken and/or required to restore any components and/or systems back to their original intended function without any delay in the way of logistics and manpower. Improved maintainability offers reduction in flight delays and cancellations, resulting in greater operational efficiency, flexibility and customer satisfaction. Therefore, accurate maintainability prediction is an important tool to allow designers to improve predict and maintainability and therefore reduce maintenance costs and increased revenues.

Every new research development proposes that one of the main targets is cost reduction. From a maintainability perspective, cost reduction is important but without compromising the aircraft safety element. Cost reductions from a maintainability perspective refer to minimising materials, logistics, and man-hours required performing the necessary maintenance tasks.

As reported by the International Air Transport Association (IATA), [1] the Maintenance Repair Organisation (MRO) spending costs were below 40 billion USD between 2002 and 2006. However, from 2007 to 2010 MRO spending costs have increased to between 40 and 50 billion USD. The report also estimated that the MRO spending costs will increase drastically from more than 50 billion USD to nearly 65 billion USD by 2020. All of these figures are illustrated in Figure 1—1. This report is based on 3,312 total fleet aircraft. The main contributors to this report are 63% from Boeing, 32% from Airbus – the biggest names in the aircraft industry – and 5% from others.

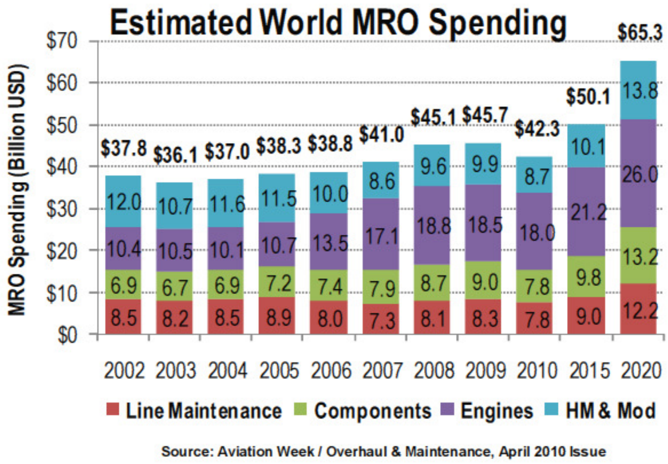


Figure 1—1 Reported Maintenance Cost Spending [1]

In terms of human factors, Graeber and Marx [2] have suggested three steps as a way to reduce, and possibility eliminate, aircraft maintenance human errors: 1) *Maintenance data should be organized in a form that will allow study of the human performance aspects of maintenance*; 2) *The gap between the maintenance community and psychology as it applies to aviation should be narrowed*; and 3) *Methods and tools should be developed to help aircraft designers and maintenance managers address the issue of human error in a more analytical manner*. They also highlighted three different errors: error reduction, error capturing and error tolerance. A lack of maintainability knowledge, awareness, and consideration does promote accident and incident problems. The UK Civil Aviation Authority (CAA) [3] and Sear [4] have reported that design faults, and maintenance and inspection efficiencies are among the top four contributors to aircraft accidents and incidents - each one contributing 13% or 12%.

Other types of maintenance related problems caused by human errors are incorrect installation of components, fitting of wrong parts, electrical wiring discrepancies (including cross-connections), loose objects (tools, etc.) left in aircraft, inadequate lubrication, cowling, access panels and fairings not secured, landing gear ground lock pins not removed before departure [5], omissions (56%), incorrect installation (30%) wrong parts (8%) and other (8%) [2], and fastenings undone/incomplete (22%), Items left locked/ pins not removed (13%), caps loose or missing (11%), items left loose or disconnected (10%), items missing (10%), tools/spare fastenings not removed (10%), lack of lubrication (7%), and panels left off (3%) [6]. The Occurrence Maintenance Scheme (OMS) is one of the examples used to identify the factors contributing to aircraft incidents, and to make the system resistant to similar errors [7].

As described in previous paragraphs in this chapter, maintenance related problems are affected by technical and non-technical factors. Technical factors refer to logistics and manpower, while non-technical factors refer to weather and workplace conditions. Technical factors are strongly affected by decisions made by designers, whereas the latter are governed by other aspects, which include those managed by the operators, such as maintenance, logistics, operations, and management. This thesis will address only those technical factors that can be influenced by aircraft designers and the role of maintainability prediction in designing for maintainability.

Designing a new product requires several elements to be considered. The elements under consideration should be able to offer better benefits than previous designs. Those potential benefits include cost reduction, error reduction, task time reduction, and improved customer satisfaction. Learning from past experiences is the best platform. For complex products, one of the important elements to be considered is the product's maintainability factors. Good maintainability consideration should be able to offer several benefits including improvement in product life cycle and cost reduction. In the aircraft industry, numerous improvements and methodologies for maintainability have been proposed. Most of the proposed methodologies are successful and offer many more benefits. However, there are still gaps and/or problems that need to be filled and solved.

Based on years of aircraft industry experience, there are a lot of historical data which are able to offer improvements in the effectiveness of particular products' design. The effectiveness of one particular product and system are dependent on the effectiveness of different design methodologies, such as Design for Assembly (DfA), Design for Manufacturing (DfM), Design for Disassembly (DfD), Design for Maintainability (DfMt), and Design for Reliability (DfR). There are many other types of design methodologies, collectively known as Design for X (DfX). The strengths and weaknesses of each individual DfX have been described by several authors such as Kuo [8], Chiu [9], Boothroyd and Dewhurst [10], and Blanchard [11; 12].

This research is interested in identifying and solving potential and existing gaps and/or problems from the DfMt perspective. DfMt effectiveness is measured and predicted through several methodologies, collectively known as maintainability prediction methodology. The effectiveness of maintainability prediction requires several others relevant elements to be considered, such as product design, accessibility, human factors, and supporting facilities (i.e. testing equipments). The improvement of maintainability prediction methodology was invented and has been validated since the 1960s. This is based on several literature reviews and maintainability related documentation identified by the author. The literature review and maintainability related documents are described in detail in chapter 2. Overall, numerous maintenance historical data (e.g. failure rate) and feedback information are available to be used for future improvement. The benefits of maintenance related data and feedback information include "...*to assess the performance, effectiveness, operations, maintenance, logistics support capabilities...*" [11] and "*Our engineering growth and potential in the future certainly depends on our ability to capture past experiences and subsequently apply the results in terms of "what to do" and "what not to do" in new design system design.*" [11]

Traditionally, the failure rate (λ) was the only input used to predict maintainability effectiveness. However, due to numerous restrictions such as data accessibility and accuracies, researchers (i.e. academicians) have found difficulties in proposing potential aircraft design improvement. This is due to several reasons, one of which could be to protect the MRO companies' reputation. The author has identified this problem and intends to investigate, identify, propose, test and validate the maintenance related feedback information. The main focus of this research is **to improve the design for maintainability through the use of historical data and information, and improved maintainability prediction**. One of the solutions is the use of historical aircraft maintenance related data – one of which is known as feedback information.

1.2 Research Questions

Based on overviews and the scenario described in the previous section, the problem statements of this research are proposed as shown in Table 1-1.

Table 1-1 Research questions

No	Research Questions
1	What are the elements involved in developing maintainability prediction?
2	How can a method to incorporate feedback into maintainability prediction in the early design process be developed, structured and efficiently used by the designer?
3	How can future aircraft design be improved through the application of aircraft maintenance related feedback information systems?

1.3 Rationale of Research Study

The purpose of this research is to critically review and investigate, and then to propose a new approach to improve the design for maintainability with particular reference to the use of feedback information. In this research, maintenance issues in the aircraft environment are investigated with special reference to maintenance task time allocation and prediction. Current practices of aircraft maintenance task time allocation and prediction using failure rate are identified based on preliminary studies of existing maintainability prediction methodologies.

The best practices aspects of the industry's solution for this complex problem are reviewed. Problems and issues in aircraft maintenance and prediction are identified, in terms of various shortcomings and the incapabilities of current processes and associated methods/techniques. The study also aims to identify possible improvements on maintainability prediction processes and any potential benefits of those improvements when implemented in an integrated system environment.

1.4 Research Aim

The aim of this research is **to develop an approach to improve the maintainability prediction for aircraft mechanical components**. This research will endeavour to extend the existing maintainability prediction approaches that are often used. The potential outcome from this research could be used as an alternative approach in order to enhance the effectiveness and accuracy of the maintainability prediction method.

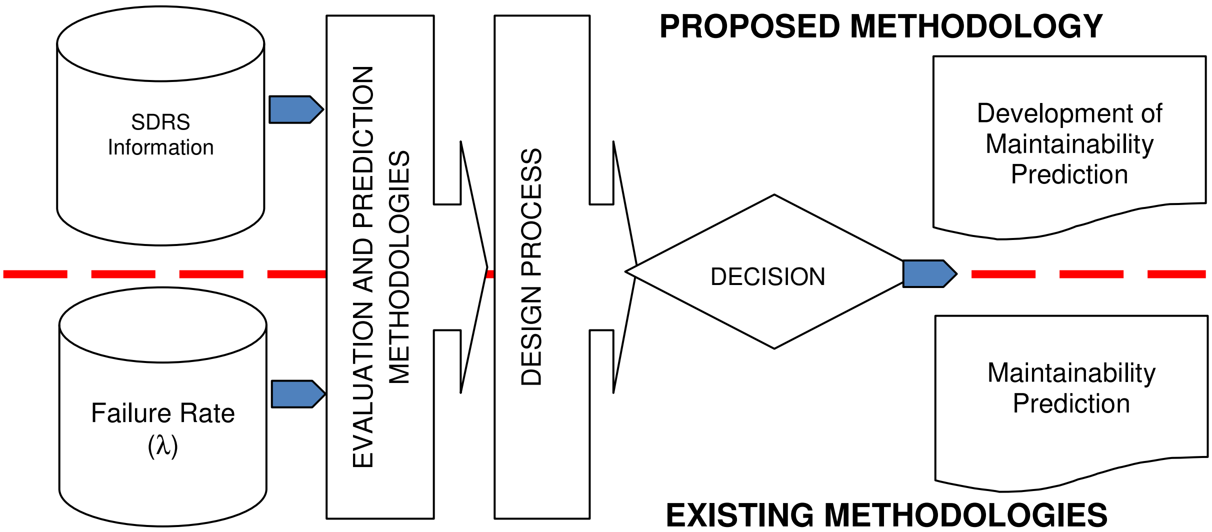


Figure 1—2 Research aim

1.5 Research Objectives

The objectives of this research were set up in line with the aim of this research. The intention is **to develop a systematic design methodology which potentially improves the maintainability prediction for aircraft mechanical components as well as maximising the use of feedback information during the design process**. This research proposes suitable feedback information processes from the end user to the designer so that the future product design can be improved. The research objectives are listed below and the research aim and questions are illustrated in Figure 1—3:

1. To propose a methodology to extract the important information from the collected maintenance data for a selected class of aircraft components;
2. To perform feedback information analyses;
3. To develop an improved maintainability prediction methodology through utilising quantitative input of feedback information;
4. To undertake case studies to demonstrate and evaluate the developed methodology.

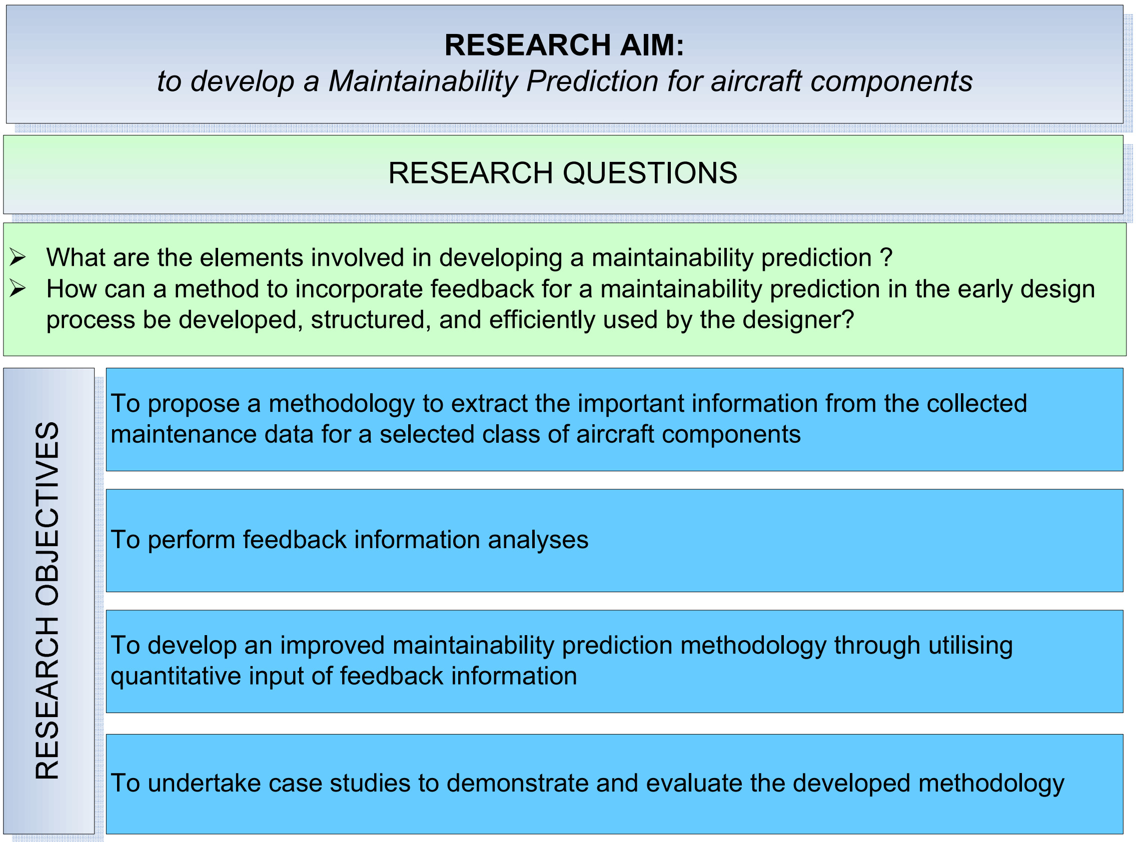


Figure 1—3 Research aim, questions, and objectives

1.6 Task Objectives

This research is divided into three main research areas: Service Difficulty Report (SDR), Maintainability allocation methodology, and Maintainability prediction methodology. Each research area has individual task objectives.

The first task objectives are: 1) **to investigate and identify the contents of various existing reliable sources of aircraft feedback information**; 2) **to identify valuable information within the Service Difficulty Reporting System (SDRS)**; and 3) **to identify potential use of the analysed SDRS**. This will offer better information for future research and development activities. The first task objective also proposes a methodology for using system feedback to improve the aircraft maintainability issue. This analysis has helped to identify the critical and sensitive systems or components of the aircraft that need more attention for improvement.

The second task objectives are: 1) **to extend the existing maintainability allocation methodology** and 2) **to identify appropriate methodology to improve maintainability allocation** method. Currently, the methodology is only focusing on the electrical and electronic-type of components and systems. The extended maintainability allocation methodology, however, focuses on the mechanical-type of components and systems; and

The third task objective is **to identify opportunities to improve maintainability prediction methodology** by using a quantitative approach. MIL-HDBK-472, Procedure III has been selected as the maintainability prediction method for this research. This is because the methodology is applicable during both the design and development stages [13] compared to other types of MIL-HDBK-472 procedure (i.e. Procedures I, II, and IV). Currently, qualitative interpretations were used to identify and allocate potential score values for each individual question. The potential benefit of the proposed technique will increase the accuracy of the maintainability prediction method. Each task objective is illustrated in Figure 1—4.

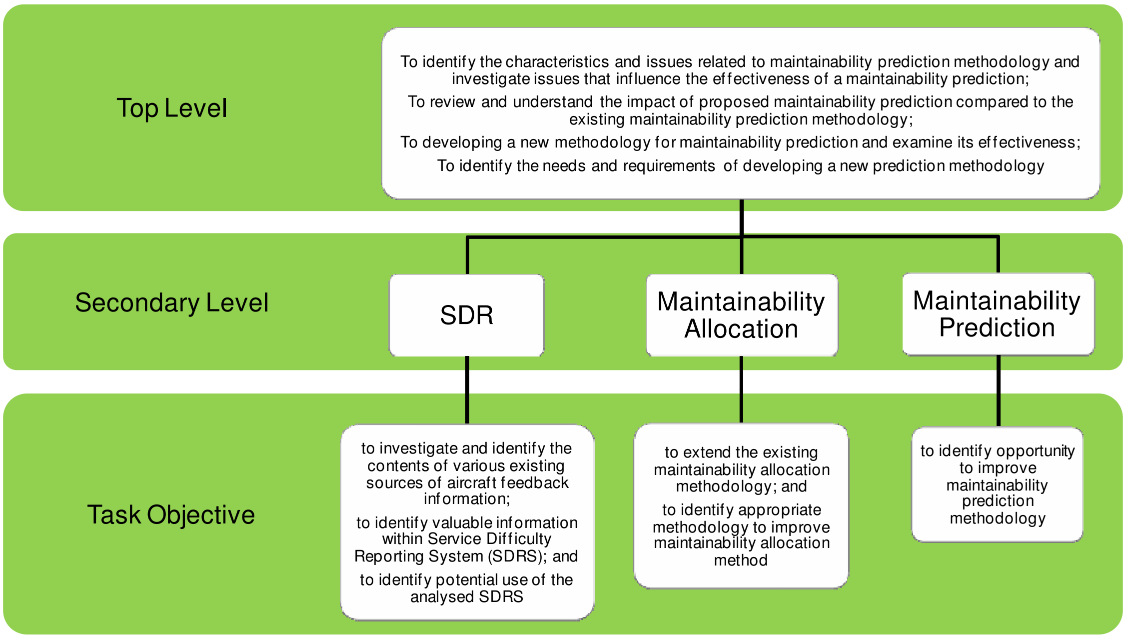


Figure 1—4 Research Task Objectives

1.7 Research Methodology

The rationale behind the research led to the development of a maintainability prediction for aircraft mechanical systems and/or components. A developed methodology can be used as an alternative method to evaluate the maintainability effectiveness at the beginning of the aircraft design process. In addition to the feedback information (SDRS) analyses, the proposed model allows us to identity and determines potential design improvement by obtaining the trend and pattern of SDRS. Figure 1—5 illustrates the main steps of the research methodology.

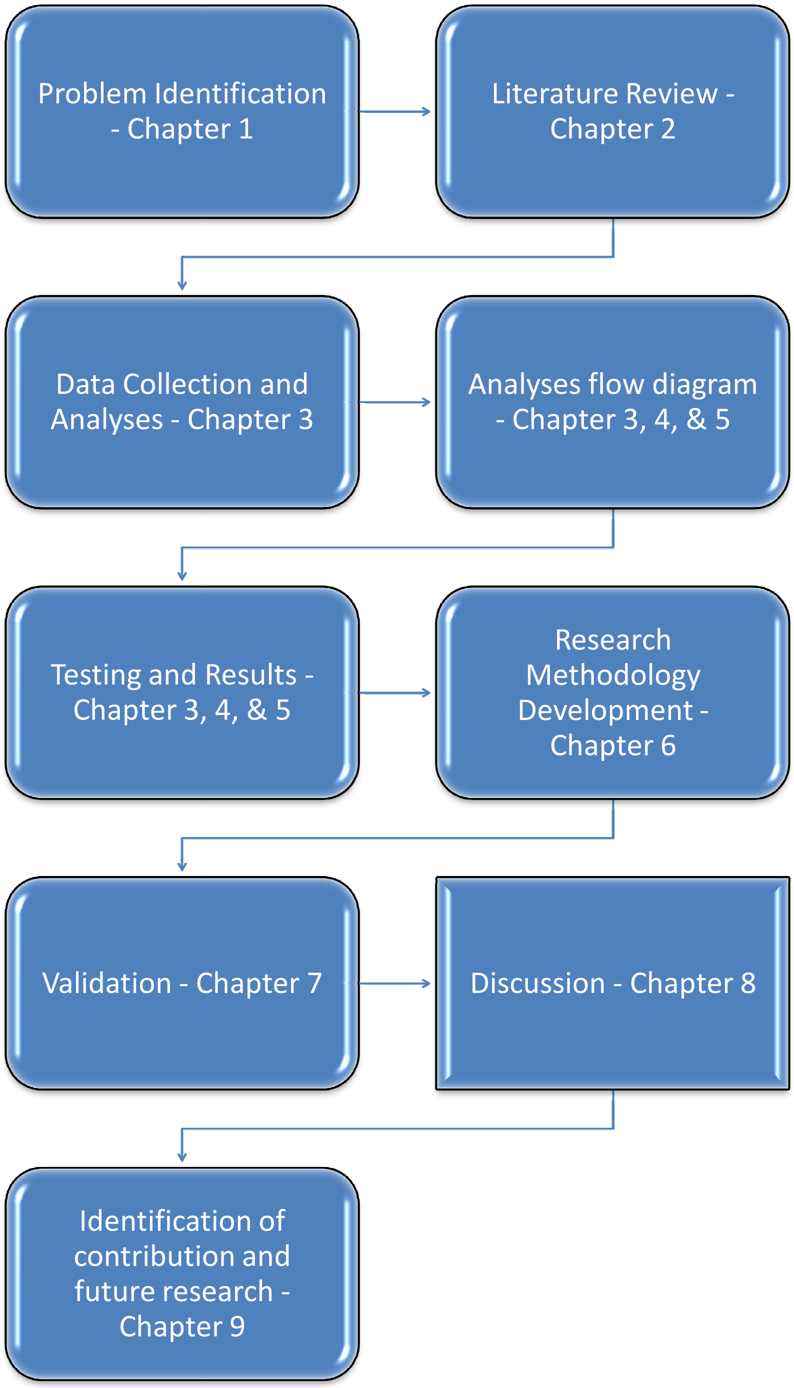


Figure 1—5 Main steps of the research methodology

1.7.1 **Problem Identification**

For several decades failure rate has been the only element used in maintainability prediction. This research focuses on utilising the aircraft maintenance feedback information known as SDRS, to identify the opportunity to convert the analysed feedback information into a quantitative form so that it can be used in maintainability prediction, and to identify the opportunity to reduce maintainability trial and error.

1.7.2 Literature Review

Relevant and related literature reviews have been carried out as well as using input from industry experts in order to find the focal point of improvement that is relevant to the problem identification statement.

1.7.3 Data Collection and Analyses

The data used to demonstrate the main objective of the study were extracted from data available from reliable government reports and trustworthy websites. Other than that, data was also extracted from reliable sources, as given by one approved Maintenance Repair Organisation (MRO) Company. A total of ten years' data sets were used. Figure 3—2 shows the generic historical data sets (i.e. SDRS) process flow. Details of the SDRS analyses are presented in Chapter 4.

1.7.4 Analyses Flow Diagram

Appropriate flow charts for SDRS data analyses, maintainability allocation, and maintainability prediction were designed. The detailed methodology process of SDRS data is illustrated in Figure 3—3 of Chapter 3. This is including the integrated methodology developed by author which is presented in Chapter 6.

1.7.5 Testing and Validation

Case studies are used for testing and validation processes in this research. The selection of case studies is to be more focused on the mechanical components, due to the fact that this research is being performed to enhance the maintainability prediction for aircraft mechanical components.

1.7.6 Methodology Development

There two main elements involved in methodology development: 1) Feedback Analyses which include identifying and analysing suitable feedback information and 2) Quantitative analyses which include maintainability allocation and prediction methodologies. The second element is to identify existing quantitative maintainability prediction methodology and propose an improved methodology utilising aircraft related feedback information. The greatest contribution of this research is through the feedback analyses and maintainability allocation methodology

1.7.7 **Validation**

The proposed methodology is tested and validated by using real industrial maintenance data and tasks time.

1.7.8 **Discussion**

Describes the potential benefits to users of the industry solution when the proposed approach and improvements are incorporated into the maintainability prediction methodology.

1.7.9 **Identification of contribution and future research direction**

At this stage the contribution and future research direction have been identified. The contributions are divided into two sections: 1) Contribution to maintainability prediction methodology, and 2) Contribution to academic theory. As well as some limitations, some successful results have been achieved from this research. There are many opportunities identified by the author with regard to the future of this research.

1.8 Research Focus

This research project focuses on both the development of a new approach to predict maintainability by using aircraft maintenance historical data, and the development of maintainability allocation. The focuses are restricted to historical data and maintainability allocation, for the following reasons:

1. Historical data are the focus because they contain rich aircraft information, both technical and non technical. The technical information refers to parts conditions and non technical information refers to the nature of those conditions.

2. The focus is on maintainability allocation in order to extend an existing method which was developed by Chiphak [14] and allow it to be applied to mechanical components.

1.9 Structure of thesis

This thesis is structured appropriately so that the identified problems, research aim, and research objectives are presented accurately and logically so that readers are able to understand the identified problems and the outcome of this research. This thesis is structured as follows:

Chapter	Title	Description
1	Introduction	Describes an overview of this research. The aim of this research is briefly explained and the research questions are presented. This section provides an overview of the maintenance problems, current practices, and issues in the documentation environment. This is followed by an overview of maintenance issues in the aerospace environment and aircraft related feedback information.
2	Literature Review	Describes and provides a comprehensive review of existing design methodologies related to maintainability; techniques used to solve the problems; various types of aircraft related feedback information and systems. This chapter provides an overview of the selected feedback information aircraft maintenance, repair and overhaul (MRO).
3	Research Methodology	Describes overall proposed methodology and techniques to be used, outlining research aim, research objectives, and briefly explaining each methodology step. Problems and issues in maintainability prediction methodology are highlighted in this section, with special reference to alternative solutions to predict the maintainability and maintenance prediction allocation methodology. An improvement for maintainability prediction processes within the selected solution is presented.
3	Use of Feedback Information for Maintainability prediction	Describes all data analyses and results achieved, and the proposed formula and method of applying the formula in order to enhanced an approach development. This research proposes possible improvements for the maintainability prediction methodology.
4	Maintainability Allocation Methodology	
5	Maintainability Prediction Methodology	
6	Integrated Methodology	
7	Validation	Presents the validation results and detailed descriptions.
8	Discussion	Presents the improvements and describes the potential benefits to users of the industry solution when the proposed approach and improvements are incorporated into the maintainability prediction methodology.
9	Conclusion & Future Research	The paper concludes with findings and suggestions for future research.

2 Literature Review

2.1 Introduction

In this chapter, the author describes several related elements to this research. These include the elements of Product Development, Design for X (DfX), Maintainability allocations methodology, and Maintainability prediction methodologies, and various types of aircraft maintenance related feedback. Information systems are presented in the following sections of this chapter. The purpose is: 1) to provide an overview of five elements which are related to this research; 2) to present the trend and current practices; and 3) to present the problems of and gaps in current practices. These problems and/or gaps found are used for further improvement or minimising the problems. At the end of this chapter, the author summarises all the literature reviews from the perspective of this research.

2.2 Product Development

There is growing interest in promoting and developing new methodologies, concepts, and approaches to improve the end phase of products. The aim is to improve and develop product development process systems to comply with the maintainability and service requirements. Maintainability is defined as:

"*The relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair and in this context, it is a function of design*" [15].

Considering maintainability during the design phase will potentially extend the life of products, reducing life cycle cost and the use of natural resources, improving the service systems, and having the potential to share product. Various studies have been carried out to improve product development during the design phase such as Design for X (DfX's); however, it has been concluded that the development of DfX's only focuses on improving the product. There are some areas that need to be improved such as approaches to be considered to design and development product to provided additional supports and services to the customers.

2.3 Design for X

Design for X is abbreviated as DfX. The main focus of the literature review in this section is to understand the methodology applied to evaluate the effectiveness of each individual DfX and further apply any good ideas to improve the maintainability prediction methodology. DfX consists of Design for Manufacturing and Assembly (DfMA), Design for Disassembly (DfD), Design for Life Cycle (DfLC), Design for Quality (DfQ), and Design for Reliability (DfR).

DfMA and DfD are reviewed because both methodologies apply the same concepts to predict the assembly and disassembly effectiveness, known as Design Efficiency (DE). DfLC is reviewed in order to understand the elements that contribute to the product life cycle. In addition, DfQ and DfR are reviewed in order to understand how both design methodologies are considered with regard to quality and reliability because both design methodologies are also important elements in maintainability prediction methodology. The next section of this chapter describes in detail each individual DfX previously mentioned.

2.3.1 Design for Manufacture and Assembly (DfMA)

Design for Manufacture (DfM) has an objective to improve product manufacturability [16; 17] through CAD-Based workstations such as Computer Aided Design and Computer Aided Manufacturing (CADCAM) [17] while Design for Assembly's (DfA) main objective is to achieve the lowest assembly cost possible [10; 18] through the number of parts required. The design effectiveness is measured by Design Effectiveness (DE), using the following formula:

$$Design\ Effectiveness = \frac{Theoretical\ minimum\ number\ of\ parts\ x\ Time}{Estimated\ total\ assembly\ time}$$

The tasks were performed using a computer program which has several elements of assembly methodology so that the designer is capable of making decisions before progressing to the final product design assembly [10; 18-20]. As a conclusion, the implementation of DfMA "*led to enormous benefits including simplifications of product, reduction of assembly and manufacturing costs, improvements of quality, and reduction of time to market*" [8; 9]. However, these approaches are only focused on two factors – part manufacturability and reduction time for assembly.

2.3.2 **Design for Disassembly (DfD)**

The objective of DfD is to reduce the time and effort required to remove components or materials from a product. As product assembly and manufacture are gradually improving, in the next phase called middle of life (MOL) [21], the element of disassembly and recycling should also be considered by designers during the design stage. Disassembly is defined as "*a process of systematic removal of desirable constituent parts from an assembly while ensuring that there is no impairment of the parts due to the process*". There are several benefits of DfD such as Operational cost reduction [22-25] and human error reduction [26]. Being aware of this scenario, several other authors have proposed a number of approaches to overcome or improve the end of product cycle such as a CAD for disassembly approach on destructive disassembly [27] and PLM (Product Life Cycle Management) [24; 25; 28-47]

In conclusion, the DfD only improves and focuses on the end-phase of the component's life and does not consider the service element for customer satisfaction.

2.3.3 **Design for Life Cycle (DfLC)**

Life cycle assessment is a major tool used for DfLC and this assessment is a "*family of methods for assessing materials, services, products, processes, and technologies over the entire life of a product.*" [9] Life cycle assessment is defined as "*an objective process to evaluate the environmental burdens associated with a product or activity by identifying and quantifying energy and materials used and wastes released to the environment*".

DfLC is one of the methodologies to reduce environmental issues other than maintenance through properly maintaining the products. Sakai et al. [48] proposed and developed "*a methodology of product life cycle design based on product life control and a product life cycle design support system using the Life Cycle Simulation system*". Aurich et al. [49] proposed a methodology to maximise product performance using the DfLC approach by analysing three different strategies known as Liability-, Function-, and Use-driven strategies. These strategies are simplified into two main design processes known as systematic product and systematic service before both design processes are combined into what is known as an integrated design process. The purpose of this process was to increase product performance. Several tools and techniques have been introduced starting from managing the product life cycle at the design phase [50] and including the cost related product life cycle [51].

From the perspective of maintainability prediction, most DfLC elements are not suitable for the maintainability prediction methodology because they are focused on environmental issues only. However the idea of maximising the performance of products offers some ideas for this research.

2.3.4 Design for Maintainability (DfMt)

There are many objectives that have been set by researchers with regard to maintainability. Collectively the maintainability objective is "*to assure that the product can be maintained throughout its useful life-cycle at reasonable expense without any difficulty*" [11] and "…. *to design and manufacture a product that is easily and economically retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair*" [15]. Maintainability "*is a key driving element in the effective support and upkeep of the system as well as providing the ability to modify and upgrade the system throughout its lifetime*". Much of the maintainability is analysed by a quantitative approach such as fuzzy theory [52; 53] vector projection methodology [54], and also by using Computer Aided Systems [52-58].

There are some authors who propose including the element of safety into Design for Maintainability [59; 60]. Therefore the author proposes including an element of human factors into the maintainability prediction to ensure it is designed in accordance with human capabilities [61-70]. Another approach to improve DfMt and maintainability prediction is through the use of an element of historical information, for which some authors use the term 'feedback' [11; 13; 14; 59; 71-80].

Maintainability effectiveness is predicted by using several maintainability prediction methodologies. The initial maintainability prediction methodology was proposed in the 1960's [13; 81] and until today remains as the standard focal point. Since then several improvements have been proposed, tested, and validated to enhance the initial maintainability prediction [15; 82-86]. One of the improvements has been through the application of Computer Aided Design (CAD) [87]. This is to ensure that maintainability can be predicted accurately by positioning maintainability elements in the right position.

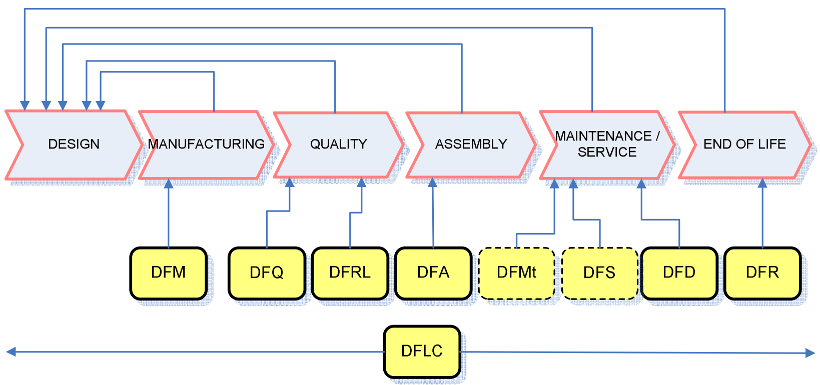
2.3.5 Design for Quality (DfQ) and Design for Reliability (DfR)

Towards the end of the product development process, some researchers propose using approaches known as Design for Quality (DfQ), and Design for Reliability (DfR). DfQ's aim is to ensure the design activities are carried out for ease of inspection and statistical analysis. All activities must comply with objectives such as: the product shall be designed in such a way as to comply with as well as exceed customer requirements and expectations, have a reduced impact on the environment, a reduced effect on the potential variation in manufacture of the product, and be capable of demonstrating product reliability, performance and technology.

The Design for Reliability (DfR) concept is to ensure that products are designed to withstand any damage or failure for a specified period of time under certain working conditions [71; 73; 88-92]. Reliability is defined as "*the probability that an item will perform a required function, under specified condition without failure, for a specified amount of time*" [93; 94]. The prediction is usually carried out using mathematical maintenance formulae such as MTBF (Mean Time between Failure), MTTR (Mean Time to Repair), MTTMA (Mean Time to a Maintenance Action), and MMT (Mean Maintenance Time) [95].

2.3.6 **Summary**

Generally, designers have to comply with all design requirements as shown in Figure 2—1. In addition there are others factors, such as regulatory, which designers must consider while trying to develop a new product.



DFM	-	Design for Manufacturing	DFMt	-	Design for Maintainability
DFQ	-	Design for Quality	DFS	-	Design for Service
DFRL	-	Design for Reliability	DFD	-	Design for Disassembly
DFA	-	Design for Assembly	DFR	-	Design for Recycle
DFLC	-	Design for Life Cycle			

Figure 2—1 Compliance with Design requirement

DfX has promoted and generated many improvements specifically on product development. The improvements also contribute to others elements such as cost reduction, time reduction, increase in production and process efficiency, and improved business strategy. Moreover, DfX promotes better design techniques to ensure that at the end of the product life there will be a lesser work load and in particular a reduction in the financial impact during the end of the life of the product.

However, each approach was only concentrating on the improvement of specific problems and did not involve whole systems [96; 97]. This means that there are still opportunity areas available for future improvement as well as extending the capability of DfX's.

The goal of DfM for instance is no longer only to make products in a proficient way, but be able to provide the capabilities that are needed by society, such as minimising material and energy consumption, pooling systems, and using take-back systems. One of the solutions is to integrate all common information during product development. This can be done throughout the design process.

There are studies that have been conducted which have concluded that a product's characteristics are mostly determined during design process, principally all the decisions made during this stage influence the lifecycle of the product [96; 98; 99]. Therefore, much more research in recent years has been dedicated to developing a fundamental understanding of the design process, improving design education, and devising tools and methods for assisting designers.

2.4 Feedback information systems – Aircraft Maintenance

2.4.1 **Introduction**

The maintainability prediction can be facilitated by systematically utilising the feedback information from past and current in-service aircraft. Learning from the past and existing experiences offers numerous opportunities for improvement – particularly a reduction in maintenance cost and errors. Therefore it is important that all relevant, existing and current feedback information is systematically collected, compiled, analysed and validated appropriately, so that necessary actions and decisions can be made. This collected information is referred to as feedback information.

The importance of aircraft related feedback information has been detected by the Boeing Company. This has been transformed into several approaches, some of which are known as the In Service Data Program (ISDP) [100] and the Flight Recorder Data Service (FRDS) [101] which provide effective information quickly and check maintenance needs. These approaches show that feedback information is valuable for further availability preparation. This indication offers the opportunity for future design methodology improvement. The important of feedback is also has been described in detail by UK CAA [7].

One of the issues for companies to consider before making the decision to buy an asset (i.e. new aircraft) is the support available from the manufacturers (i.e. maintenance and service issues). This clearly indicates that in order for products to be manufactured and to be competitive in the global market, several issues have to be considered and carefully analysed. One of these issues is the product's maintainability. Therefore, based on the overall description in the previous sections, the following research questions are posed as the basis of the research problem.

Feedback information can be utilised to improve future product development as well as safety. These data are also used to determine maintenance activities [102]. The trends and behaviour of previous and/or existing products are analysed and therefore assist with appropriate decision-making for future improvements. This is to ensure that the determined objectives have been met. The types of information collected are the failure types, failure modes and frequencies of failure, and/or replacement and maintenance trends. The information is then evaluated and used to answer the following common questions, such as *'Where are we now?', 'What should we do now?', 'Why has this happened?' and 'How can we improve this situation?'*

2.4.2 **Safety improvement from better maintenance data**

To date, many efforts have been proposed by aviation regulatory authorities and aircraft manufacturers to improve the safety of aircraft. These have been carried out through the development of various types of programs. Generally, the programs developed are to reduce human error, such as Maintenance Error Decision Aid (MEDA) [103-106] and Maintenance Error Management Systems (MEMS) [107], and to improve future aircraft design as well as maintenance activities and documentation such as the Airworthiness Directive (AD) and Service Bulletin and Letter (SB/L).

2.4.3 **Reliability, Availability and Maintainability development data**

Other types of programs developed, including Data Reporting, Analysis and Corrective Action Systems (DRACAS) [108], are designed to enhance Reliability, Availability and Maintainability (RAM), Service Difficulty Reporting Systems (SDRS) [109], Air Accident Investigation Branch (AAIB) [110], Aviation Safety Reporting System (ASRS) [111], and Aviation Safety Information Analysis and Sharing (ASIAS) [112]. The purpose of most of the developed programs is to gather as much information as possible to be evaluated for further required actions. This includes identifying any potential improvements as well as identifying the current trend of the developed products.

2.4.4 **Other data system**

Other potential sources of feedback information are the monitoring systems known as the Health Monitoring System (HMS) and Condition Monitoring System (CMS). The information is collected at the stage when the equipment or systems are being operated, and the information is collected through feedback loops. Feedback is generally known as the information which comes from the output section and is looped back to the input section.

2.4.5 **Sources of Feedback Information**

This section describes some of the existing sources of aircraft maintenance related feedback information. This is available from a range of different types of sources, including historical data, item design and/or manufacturing data, data recorded during testing, and field use data. The main aircraft maintainability and maintenance related sources of feedback information are reviewed and discussed in this section. The objectives are:

1) To explore the type of information collated in the sources;
2) To explore the strength of the developed feedback program; and
3) To acquire any potentially useful information that can be used for DfMt improvement.

The role of mandatory and non mandatory aircraft documentation related to maintenance activities such as Airworthiness Directives (ADs), Airworthiness Notices (ANs) and Service Bulletins (SBs), will also be explored. Some of the potential sources of aircraft maintenance related feedback information are discussed in the following sections.

Table 2-1 provides a summary of the information that is collected by the various historical information or feedback systems. The Service Difficulty Reporting System (SDRS) contains much more information than other types of feedback systems. The author has decided to use and analyse the SDRS for the purpose of this research. This is to ensure that a detailed investigation can be made of the affected aircraft.

Table 2-1 Summary of aircraft related feedback information

Category	Feedback Information Types	Maintenance Error Decision Aid (MEDA)	Maintenance Error Management Systems (MEMS)	Aviation Safety Reporting Systems (ASRS)	Air Accidents Investigations Branch (AAIB)	Service Difficulties Reporting Systems (SDRS)	Service Bulletin / Service Letter (SB / SL)	Airworthiness Directives (AD)	Problem/Failure/Data Reporting, Analysis, and Corrective Action System (PRACAS/FRACAS/DRACAS)
Focus	Human	X	X						
	Aircraft			X	X	X	X	X	X
General	Date and Time	X			X	X	X	X	X
	Individual Information / Involve / Experience	X		X	X	X		X	X
	Individual Involve (Pasenger, Flight Crew, Mechanic, Engineer, etc.)								
	Organisation / Regulatory	X		X	X			X	X
	Manufacturer	X		X	X	X	X	X	
Aircraft	Types	X		X	X	X	X		
	Model (Aircraft / Engine)	X		X	X	X	X		
	Registration / Nationality	X		X	X	X	X		
	Zones Information					X			
	Flight Information (From / To)				X				
	ATA / JASC Code	X				X			
Inputs	Incident	X	X	X	X	X	X	X	X
	Accident	X	X	X	X		X	X	X
	Maintenance					X	X	X	X
	Manufacturing/Processes (Corrosion / Crack)					X			
Application	Compliances							X	
	Effectivity (Which Aircraft affected)							X	
	Problem (s) type			X		X			X
	Problem (s) Detection methods			X	X				X
	Problem (s) Location / Stage of Operation			X	X	X			X
	Problem (s) Sympton Mode / Condition			X	X	X			X
	Problem (s) Precautionary			X		X			
	Problem (s) Impact to others			X					X
	Improvement		X					X	
	Part Number					X	X	X	X
Product/Engine/Propeller	Part types					X		X	
	Serial Number					X	X		X
	Manufacturer					X			
	Model Number					X	X	X	X
	General Information						X		
	Procedures							X	
	Supercedure							X	

Most feedback provides information about *what happened?* (i.e. Incident and Accident), and through detailed investigation will be able to offer several clues to reviewers for them to perform the necessary investigations into the problems. At the same time they will be able to solve and improve the problems in the form of prevention and/or improvement. Among these sources of feedback information, the ADs offer the most information in order to highlight any unsafe conditions. However, a great deal of component information comes from Original Equipment Manufacturer (OEM). The OEM normally works closely with aircraft manufacturers and customises the designs based on the aircraft manufacturer’s needs. Another source of information is available from equipment repairs and overhauls organisations.

2.4.5.1 Maintenance Error Decision Aid (MEDA)

Maintenance Error Decision Aid (MEDA) was developed to determine *"the factors that contribute to maintenance errors and taking corrective actions to eliminate or reduce the probability of future, similar errors"* [105]. These are carried out based on the philosophy "*that maintenance technicians do not make errors on purpose, that errors result from a series of related contributing factors, and that these factors are largely under management control and, therefore, can be changed"* [103-106]. Traditionally, the prevention and correction methodology has focused on "blaming and improving" human errors. MEDA consist of five sections, as follows:

Section 1 – General Information
Section 2 – Event
Section 3 – Maintenance Error
Section 4 – Contributing Factors Checklist
Section 5 – Error Prevention Strategies

The process in MEDA consists of five stages: event, decision, investigation, prevention, and feedback [104]. In terms of design, there is much information that can be used by the designer at the design stage which could also lead to future error reduction. The information obtained from Sections 3 and 4 of MEDA provides a great deal of useful information for future product development [113].

One concern is that designers do not have much time to review and analyse such information. An appropriate strategy is, therefore, required to reduce the complications within such information. There are strategies that have been proposed by CAA to ensure the feedback information is optimised and utilised. Although the strategies are specifically proposed to reduce human error, they can, however, still be applied to design activities. There are three main strategies that have been highlighted to reduce human errors, that include: "1) *Maintenance data should be organized in a form that will allow study of the human performance aspects of maintenance, 2) The gap between the maintenance community and psychology as it applies to aviation should be narrowed, and 3) Methods and tools should be developed to help aircraft designers and maintenance managers address the issue of human error in a more analytical manner"* [3].

2.4.5.2 Maintenance Error Management Systems (MEMS)

Maintenance Error Management Systems (MEMS) are described in CAA Airworthiness Notice 71. The aim is to understand and examine *what* and *why an* *event happened*. The objective is "*to identify the factors contributing to incidents and to make the system resistant to similar errors*" [107]. The aim is not restricted to knowledge of *what* happened, but also to solve *why* it happened, and thus offer opportunities to minimise recurrence. The system is used by large commercial aircraft maintainers to develop systematic procedures to identify potential errors and occurrences. This scheme claims that human elements are the major contributors to maintenance errors. Leaflet 11-50 defines the maintenance error as *"one of the safety objective restriction due to failures to perform the necessary expected action appropriately*" [107].

2.4.5.3 Aviation Safety Reporting Systems (ASRS)

The ASRS was developed by NASA to identify the potential causes of aircraft accidents. The information is available online for public review [111]. The methodology encompasses the collection of and analyses and responses to any type of aviation safety incident report. The objective is to reduce and prevent further aircraft accidents. All the ASRS data are used to solve existing insufficiencies and discrepancies, to provide recommendations to appropriate authorities, and to improve human factor issues regarding aircraft. ASRS encompasses four types of reporting inputs: 1) General, 2) Air Traffic Control, 3) Maintenance, and 4) Cabin.

This reporting system focuses on the maintenance types of reporting inputs in seven main categories, namely Time and Location, Experience, Contribution Factors, Consequences/Outcome, Aircraft and Airworthiness Status, Mission, Reporting Organisation, in addition to Type of Aircraft and Engine. Although this source of feedback contains much information, such as the causes of accidents, the designer has to put more effort into analysing the information using appropriate analysis tools. This is to ensure that the relevant information is captured appropriately for future design improvements.

2.4.5.4 Air Accident Investigations Branch (AAIB) accident reports

The aims of the AAIB accident reports are "*to determine the circumstances and causes of the accident and to make safety recommendations, if necessary, with a view to the preservation of life and the avoidance of accidents in the future",* and *"It is not to apportion blame or liability*" [114]. This is associated with the International Civil Aviation Organization (ICAO) requirements stated in Annex 13 of the Aircraft Accident and Incident Investigation. Annex 13 is one of the documents controlled and prepared by the ICAO.

The main intention of this document is to outline international standards and recommended practices to prevent aircraft accidents as well as aircraft safety enhancement. Investigations encompass various aspects such as flying procedures and techniques, and engineering factors such as aircraft airworthiness and maintenance techniques. Typical data collected are: 1) Type of Aircraft and Registration; 2) Type of Engines and Year of Manufacture; 3) Date & Time (Coordinated Universal Time known as UTC) and Location; 4) Type of Flight; 5) Persons on Board; 6) Injuries; 7) Nature of Damage; 8) Commander's Licence, Age, Flying Experience; and 9) Information Source.

The information is easily accessible and can be downloaded from the above mentioned webpage [111]. Unfortunately, due to large amounts of information contained in the database, it is often difficult for readers to trace the way in which particular conclusions have been reached. Due to this issue, Johnson [115] proposes a mathematical solution to simplify the findings of accident investigations and claims that: *"These techniques enable analysts to formally demonstrate that a particular conclusion is justified given the evidence in a report. In doing so, it is possible to identify missing pieces of evidence, to identify ambiguities and to determine which items of evidence are critical to particular lines of argument"*.

As a conclusion, Johnson [115] proposed design techniques to support the design of safety-critical applications using Computer Aided Engineering (CAE) which "*helps to ensure that findings about previous failures are propagated into the subsequent development of future systems"*. Meanwhile, Smart [116] examined the trust of the public and the aviation industry towards AAIB, as well as its ability to conduct independent and objective investigations. He concludes that both the quality and culture of the organisation influence the public's trust in accident investigation.

2.4.5.5 Service Difficulty Reporting Systems (SDRS)

SDRS is another source of feedback information which collects data and focuses on aircraft service difficulties [117; 118]. The information is used to gain a better understanding of the problems of service difficulties and can be used to investigate the trends of difficulties. The data gained from the SDRS can potentially contribute to future product development as well as safety factors. The information is submitted by using FAA Form 8070-1.

This contains three major sections: Major Equipment Identification; Problem Description, including the part name, part number, part condition and part/defect location; and, Information from the individual submitting the information. SDRS is categorised in accordance with the Joint Aircraft Components and Systems (JASC) Code. The JASC Code is divided into four major components: Aircraft, Airframe, Propeller/Rotor Systems, and Powerplant Systems.

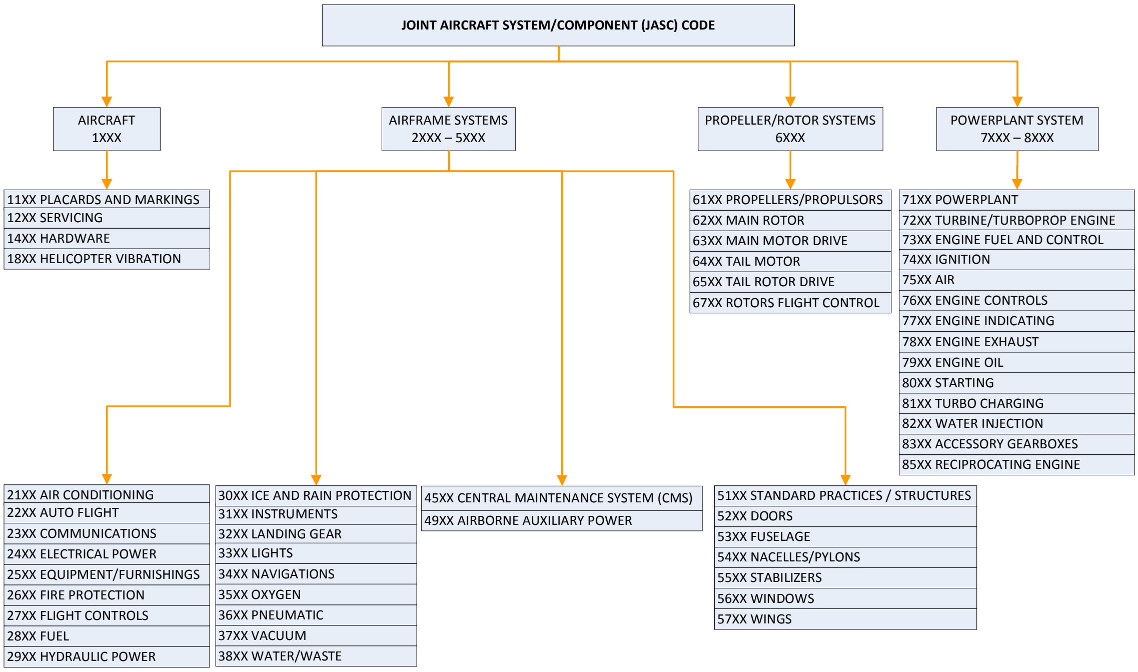


Figure 2—2 List of JASC Code (Illustration prepared by author)

2.4.5.6 Service Bulletin/Service Letter (SB/SL)

The Service Bulletin (SB) contains information for any modification to the existing products or systems to improve the safety and efficiency of the aircraft. Service Bulletins are usually supplied by either airframe or engine manufacturers for any type of improvement or modification made.

The aim is to improve the safety and operation of the affected aircraft. In terms of the design stage concerned, this type of information should be kept or stored as required by regulatory authorities (i.e. EASA Part 145) so that all the information can be used for future product development. An example of regulatory requirement is shown in Appendix A. In addition to SB, a Service Letter is also supplied by the manufacturer to describe maintenance actions without equipment modifications. SL is a letter to assist maintenance personnel to perform their duty according to the SB.

2.4.5.7 Airworthiness Directive (AD)

Airworthiness Directives are one of the regulatory documents for aircraft maintenance. These documents are issued by airworthiness authorities for any unsafe conditions for existing aircraft, components and systems [91]. They are mandatory documents that must be complied with by affected aircraft, products and systems. All paperwork should be kept or stored in accordance with regulatory requirements for future reference. Usually, an AD is a result of several types of investigation, including accident and incident investigations. Typically, an AD consists of:

1. A description of the unsafe condition;
2. The affected products;
3. Type of actions to comply;
4. The effective date to comply;
5. Sources of reference;
6. A suggestion for an alternative solution.

It is clear that the AD is a document which contains information that is relevant to safety requirements, and therefore can be considered as one of the sources of feedback information that should be used for future design improvement. However, it is not clear how the information can be compiled, analysed and transformed into design enhancement.

2.4.5.8 Problem/Failure/Data Reporting, Analysis and Corrective Action Systems (PRACAS/FRACAS/DRACAS)

Problem Reporting, Analysis and Corrective Action Systems (PRACAS), and Data Reporting, Analysis and Corrective Action Systems (DRACAS) are the closed-loop systems which ensure all feedback information for further action and improvement is provided, including discrepancies and failures which happen during design, testing and manufacturing [108]. The tool is used by the Reliability and Maintainability (RAM) engineers, specifically at the UK Ministry of Defence (MOD), to evaluate the potential improvements of existing product design and development. DRACAS is a new terminology used by the MOD, which was previously known as Failure Reporting, Analysis and Corrective Action Systems (FRACAS). This is because the scope of DRACAS is much wider, specifically regarding the types of data collected relative to FRACAS.

Another category of feedback information is known as Problem Reporting, Analysis and Corrective Action Systems (PRACAS) [119]. PRACAS was developed by NASA specifically for an aeronautical perspective. Typical types of information collected are:

1. The location of failure;

2. When the failure was detected and/or discovered;
3. Applicable part number, serial number and model numbers;
4. Operation being performed;
5. Failure symptom/mode;
6. Particulars of individual who performed the duty;
7. The impact of the failure occurring to systems and/or other components.

Regardless of what type of terminologies and acronyms are used, the concept of this type of feedback collection methodology is known as closed-loop analysis and the correction action process, and offers opportunities to track and report problems or failures [69; 74; 75]. Consequently, the tracked and reported problems can be analysed by using appropriate analysis tools to improve performance as well as enhance the product design.

2.4.6 **Other sources of feedback**

Other sources of feedback information which could be used for future aircraft design improvements are data collected from the monitoring systems. Monitoring is an activity carried out through the observation of particular systems. The main purpose of monitoring systems is for health monitoring and preventive maintenance. Preventive maintenance is an action to ensure the systems operate at a specified level of required performance. There are several types of monitoring systems, which include: 1) Aircraft Engine Health/Monitoring Systems; 2) Aircraft Tyre Monitoring Systems – which aim to monitor the inflation pressure or temperature of an aircraft tyre; 3) Aircraft Systems Monitoring Systems (i.e. Hydraulic Pump); 4) Structural Health Monitoring Systems (SHMS); and 5) Integrated Vehicle Health Monitoring (IVHM).

Generally, monitoring systems encompass two major elements: computer and electronic components. The combination of these two elements allows the necessary information to be collected during the monitoring stages. Some of the benefits of monitoring systems include the ability to improve aircraft availability, minimise maintenance and eliminate errors. The collected information is considered as feedback information which may be used to determine the life cycle of the systems or components.

Monitoring systems are able to contribute to DfM as well as maintainability improvement such as cost reduction [120] and reduction in maintenance time [121]. However, the extent to which the information is used and its contribution to future product development is still not clear. This information needs to be channelled or transformed into better information for designers to make adjustments and future improvements.

2.5 Existing maintainability prediction methodologies

Maintenance plays an important role in the aircraft industry [67; 122]. The trend of maintenance and maintainability in the aircraft industry has also changed tremendously [123]. The literature review presented in this report focuses on the maintainability prediction methodologies. Most of the reviewed methodologies are extracted from reliable sources which are commonly used in the aircraft industry – both civil and military. The rest of the literatures [124-126] explain the important of MIL-HDBK-472 and present the techniques of each individual procedure effectively. Maintainability also predicted by using other approaches known as the maintainability index [59; 85; 127; 128].

This section describes the existing maintainability prediction methodologies. The research will be using the element of historical data (i.e. feedback information) to develop an alternative maintainability prediction method for a new approach to the maintainability prediction at the design stage. The existing maintainability predictions were reviewed and identified those most closely related to design activities.

The identified maintainability prediction should have elements of design within the prediction methodology. The following section describes the existing types of maintainability prediction methodologies.

2.5.1 **MIL-HDBK-472**

The philosophy of this type of maintainability prediction is that "*the systems failures are primarily due to the malfunction of replaceable items and therefore, the time cycle for the various steps required to replace these items is a measure of downtime which is a parameter of system maintainability*" [129].

MIL-HDBK-472 consists of four main procedures. The list and a description of each procedure are shown in Table 2-2. The type of maintainability prediction researched by the author is the one that is suitable to assist the designer to design and perform the necessary improvement at the design and development stages.

The author's philosophy is that a good maintainability prediction method is the one that is user-friendly, practical, and possibly consists of an element of historical data.

Table 2-2 List of MIL-HDBK-472 procedures [13]

Procedure	Description
I	" …applicable to predict flight-line maintenance of airborne electronic and electro-mechanical involving modular replacement at the flight line.";
II	"…applied to predict the corrective maintenance time.";
III	"The procedure is adaptable for performing maintainability predictions during the Design and Development stage.";
IV	"Time analysis can be performed as soon as sufficient system/equipment definitions exists."

Table 2-3 shows the summary of all four types of maintainability prediction procedures. The purpose of this table is to identify and pull out the important elements as possible and at the same time contribute to the author's decision making. The author decided to choose the procedure that has an element of design characteristics. In the initial stage of consideration, the author found three procedures (i.e. I, II, and IV) had a few contributions to design elements although all procedures contributed to the maintainability prediction methodology. Procedure III was, therefore, chosen for the following reasons:

1. Consists of elements of design such as accessibility, tool manipulation, and visual;
2. Consists of elements of facilities such as sources of testing, human resource requirement, and special tools and/or equipment required;
3. Consists of elements of identification for improvement and modification;
4. Consists of elements of the human factor.

Procedure	Study	Discipline	Goal	Methodology	Analysis Methods
I	Prediction of flight-line maintenance of airborne electronic and electro-mechanical systems	*"….to predict system downtime of airborne electronic and electro-mechanical systems involving modular replacement at the flight – line."*	To determine the prediction of flight-line maintenance of airborne after the design concept has been established provided fundamental data are available	Data analyses and prediction	The distribution of System Downtime
II	Prediction of the corrective maintenance time and active maintenance time	*"….describes the method and techniques which are used to predict Corrective, Preventive, and Active Maintenance parameters."*	Method is suitable for shipboard and shore electronic systems/equipment, mechanical equipment or systems if the functional levels can be established, however **<u>ONLY</u>** applicable during the final design stage	Data analyses and prediction – the table was produced based on 300 observations of maintenance activity in the US fleet and divided into nine categories including Localisation, Isolation, Disassembly, Interchange, Reassembly, Alignment, and Checkout	Equipment Repair Time (ERT) $$ERT = \frac{\sum(\lambda Rp)}{\lambda} = MTTR$$ Corrective Maintenance (Mc) $$Mc = \frac{\Sigma\,(\lambda Mc)}{\Sigma\lambda}$$ Preventive Maintenance (Mp) $$Mp = \frac{\Sigma\,(fMp)}{\Sigma f}$$ Active Maintenance (M) $$M = \frac{(\Sigma\lambda)Mcti + (\Sigma f)Mptj}{\Sigma\lambda ti + \Sigma ftj}$$ Maintainability Index (MI) $$MI = \frac{(\Sigma\lambda)Mcti + (\Sigma f)Mptj}{t}$$
III	Prediction of the mean and maximum corrective maintenance downtime for ground electronic systems/equipments."	*"… describes a method of performing a maintainability prediction of ground electronic systems and equipment by utilising the basic principle of random sampling."*	Repair by replacement	Data analyses and prediction by using score values for three checklists, including design, facilities, and human factors and substitution of these score values into a regression equation, and the result is an estimate of downtime	$Mct = antilog\,(3.54651 - 0.02512A - 0.03055B - 0.01093C$
IV	Prediction of the mean and/or total corrective and preventive maintenance downtime systems/equipments	*"… based on the use of historical experience, subjective evaluation, expert judgement, and selective measurement for predicting the downtime of system/equipment."*	Task time estimation combined to predict overall system/equipment	Data analyses and prediction – the input of data is based on historical experience and expert judgement	Mean Corrective Downtime – MCDT; Mean Preventive Downtime – MPDT; Total Mean Downtime - TMDT

Table 2-3 Summary description of MIL - HDBK - 472 procedures [13] (Simplified by Author)

Procedure II has considerable application for this research because the approach has been formulated into nine different levels: Part, Stage, Subassembly, Assembly, Unit, Group, Equipment, System and Subsystem. The author's concern with procedure II was about what to do if the maintainability prediction were to be more than the allocation time because the designer did not know which design element needed to be changed or altered (i.e. redesigned).

In procedure III, if the maintainability prediction value is more than the allocation time, the designer may look back to the lowest score value in each checklist – A, B, or C. Procedure III offers score values of 4, 3, 2, 1 and 0, where the highest score is allocated to the most maintainable element, and the lowest score is allocate to the least maintainable element. To illustrate the score value allocation as described, the following Checklist A is used.

Table 2-4 Checklist A - Question 1

Number	Scoring Physical Design Factors	Scores	Value
CHECKLIST A - PHYSICAL DESIGN FACTORS			
1	Access (External)	Access adequate both for visual and manipulative tasks (electrical and mechanical)	4
		Access adequate for visual, but no manipulative	2
		Access adequate for manipulaltive, but not visual	2
		Access not adequate for visual or manipulative	0

The first question is asking about the external accessibility. If the mechanical component has both elements of visual and tool manipulation, the final score is 4, because the highest score offer is equal to 4. Meanwhile if the mechanical component has no indication of visual and tool manipulation, the score is 0, meaning the least maintainability element. Based on the previous paragraph's example, this shows that procedure III does have a design element that is useful for this research.

The MIL-HDBK-472, procedure III, consists of design checklists and scoring values which are used to determine the Mean Time to Repair (MTTR). The checklists are categorised into three types of element related to design parameters: the Product *"the physical configuration of the system";* the Facilities *"the facilities provided for maintenance by the design";* and the Human Factors *"the degree of maintenance skills required of personnel charged with the repair responsibility"*.

Each element is evaluated by using quantitative score values for the purpose of maintainability prediction. Collectively, the score value starts at 0 and goes to a 4 rating score. The higher the score value equivalent, the better the contribution to the design element as well as to the maintainability prediction. The lowest values scored equivalent to the worst design element. This offers the opportunity to redesign or review the score value for a better MTTR value at the end of the prediction evaluation.

2.5.2 **MIL-HDBK-470**

The procedure presented in this section is from the MIL-HDBK-470A, Appendix D, and Procedure V. It was developed to overcome deficiencies identified in Procedures I, II, III, and IV within the MIL-HDBK-472 [130]. However, the aim still remains the same, i.e. to perform the maintainability predictions which include the modern automated maintainability analyses tools.

2.5.3 **Maintainability analyses and prediction**

The goal of maintainability prediction was performed "*an assessment of the design of the systems (and its components) from a maintainability perspective*" [13]. The objective of this is to ensure each part and component is designed in accordance with maintainability criteria. The accuracy of the maintainability prediction is dependent on the accuracy of the input data, availability of accurate historical data, evaluation techniques or methodology used, and suitable knowledge to ensure the prediction can be performed from various directions or perspectives.

Maintainability analysis is always used to analyse the systems. The analysis is based on available components and any other related elements contributing to the success of the function of systems. There are several existing maintainability analyses and predictions available for reference. Some of these are Maintainability Prediction [15], Designing and Develop Maintainability Products and Systems [130], and Maintainability Verification, Demonstration, and Evaluation [131]. Normally the analyses are conducted after the designed has been completed.

2.5.4 **Maintenance Time**

Maintenance time is always associated with maintainability characteristics. Design for Maintainability (DfM) is also associated with three major DfX's namely Design for Disassembly (DfD), Design for Assembly (DfA), and Design for Reliability (DfR). MIL-HDBK-472 which was published in 1966 is used as a major reference for prediction maintainability [132]. There are many papers published associated with time for removing items which refer to DfD and DfA. However, DfR is always associated with Failure rate (λ) and Availability as an element to predict the reliability of specific components.

Fielding [132] mentioned that Safety, Reliability and Maintainability are three major elements that have to be considered in gaining the effectiveness of product development. The questions to answer are: How can all of these major elements be connected together and contribute to the effectiveness, and How can time be associated with that effectiveness?

Time estimations for maintainability can also be calculated through a combination of DfD and DfA. There are several factors from DfD and DfA which are able to contribute to time for maintainability prediction. This is carried out by using Number of Parts, Tools Manipulation Factors, and Maintainability Characteristics. All of these three elements are then multiplied to obtain the Design Efficiency. Does Design Efficiency give the indication that the aim of maintainability is achievable? Figure 2—3 and Figure 2—4 show different types of time associated with maintenance.

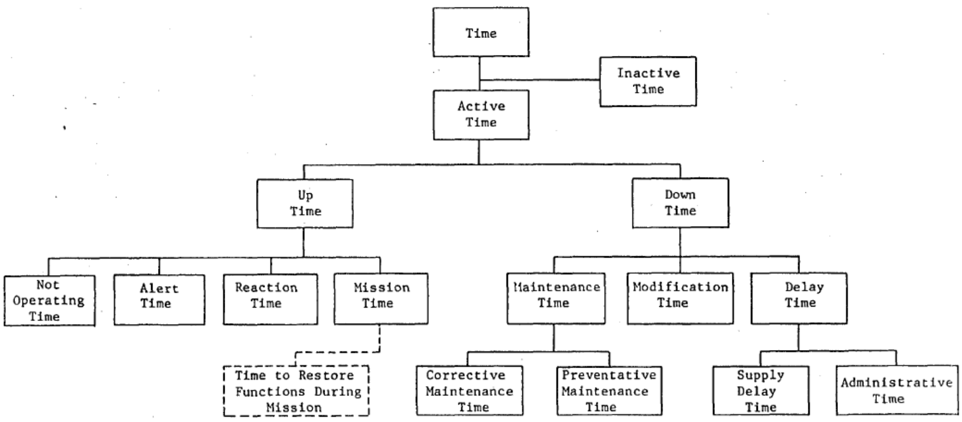


Figure 2—3 Time Relationship [133]

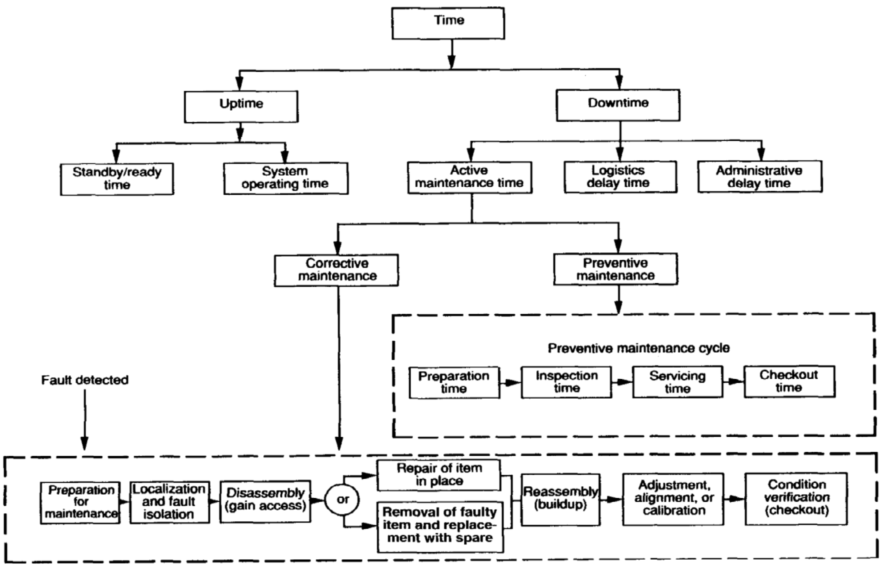


Figure 2—4 Maintenance time relationship [12]

Boothroyd et al. [10] provided three important elements to consider during the decision to evaluate DfA Design Efficiency. DfA also has been used in the aviation industry and proved to be successful [20]. DfD also uses the same concept as DfA. The three elements of DfA were used during design practices and evaluation [32-34; 36; 37; 41; 42; 45; 134].

2.5.5 Maintainability relationship

Figure 2—5 shows some of the elements involved in ensuring the aim of maintainability is achievable. Those elements are safety, manufacturing, human engineering, diagnostics and maintenance, and logistics support. Each one of these elements has it is own strengths. In term of priorities, this is difficult to determine because each one of these elements is connected to all the others.

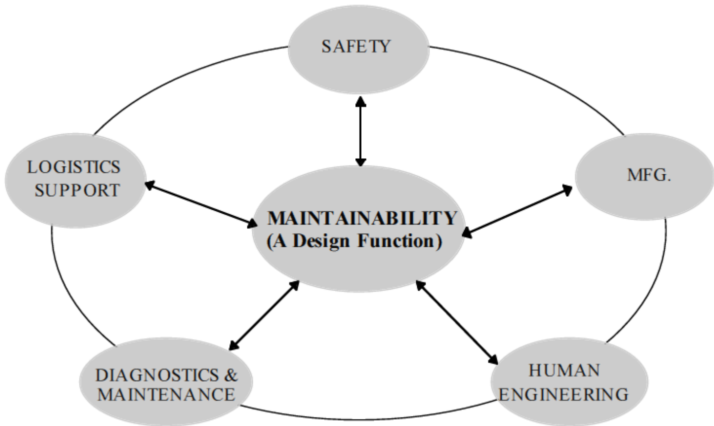


Figure 2—5 Some key elements of the Maintainability relationship [130]

2.5.6 Design for maintenance strategies

This started with the development of Maintenance Steering Group (MSG)-1 which was to improve the development of MSG 2. MSG 3 came after that with more improvements having been made. MSG 2 was based on process-oriented while the improvement through to the MSG 3 was focused on task-oriented. The trend has grown with the invention of Maintenance-by-the-hour (MBTH) [135], Maintenance Free Operating Period (MFOP) [136; 137], and Failure-Free Operating Period (FFOP) [138].

Generally this type of strategy is defined as "*a period of continuous operation without the need for logistic support*" [139]. An MFOP *"is a period of time during which there is no need for scheduled or unscheduled maintenance*" [109].

2.5.7 **Elements of maintainability**

The following Table 2-5 shows elements of maintainability:

Table 2-5 Maintainability Elements (Compiled by the Author)

Bluvband and Zilberberg [140]	Bineid and Fielding [141]	Boyd [142]	DoD- HDBK-791 [62]	MIL-HDB-472, Procedure II [129]	Montgomery and Marko [130]
1. Accessibility; 2. Visibility; 3. Testability; 4. Complexity; 5. Interchangeability; 6. Identification; and Labelling; 7. Verification; 8. Simplicity.	1. Accessibility; 2. Assemblability; 3. Standardisation; 4. Simplicity; 5. Identification; 6. Diagnosability; 7. Modulisation; 8. Serviceability; 9. Testability; 10. Parts/Components; 11. Reliability.	1. Reach, clearance, and strength; 2. Space needed for manipulation of tools; 3. Restrictive effects of apparels; 4. Demands for visibility; 5. Conditions that reduce sense of balance and position; 6. Demands for fine control of movements.	1. Simplicity; 2. Accessibility; 3. Standardisation; 4. Modulisation; 5. Identification; 6. Testability; 7. Ergonomics.	1. Localisation; 2. Isolation; 3. Disassembly; 4. Interchange; 5. Reassembly; 6. Alignment; 7. Checkout.	1. Localisation; 2. Isolation; 3. Disassembly; 4. Interchange; 5. Reassembly; 6. Alignment; 7. Checkout; 8. Start-up.

Although the various authors have different perspectives on the element of maintainability, it can be concluded that there are two important elements to be considered. These are the **times** to perform the necessary maintenance actions and **error/failure detection** which includes the methodology to detect an error when failure occurs. Based on these two elements, others elements such as accessibility, verification, removal and replacement etc. can be considered as supportive elements. This is to ensure the two important elements,, as mentioned previously, can be minimised.

2.5.8 Maintenance tasks for airframe systems

Under MSG-3, maintenance tasks for airframe systems are divided into 8 tasks and Table 2-6 shows the detail.

Table 2-6 Maintenance Tasks for airframe and structural items [143]

Maintenance Tasks		Structural Inspection
Airframe Systems	Structural Items	
1. Lubrications; 2. Servicing; 3. Inspection; 4. Functional Check; 5. Operational Check; 6. Visual Check; 7. Restoration; 8. Discard.	1. Environmental deterioration; 2. Accidental damage; 3. Fatigue damage.	1. General Visual inspection; 2. Detailed inspection; 3. Special detailed inspection.

The impacts of not considering maintainability as a major element for the components' life extension is broadly explained by several researchers [144; 145]. Although these papers did not specifically explain in detail the contribution of maintainability to the life cycle they did give a better view of the impact on cost as well as on "human life". Alonso-Rasgado et al. [146] explain in detail the combination of several elements of DfX in order to achieve a Total Care maintenance strategy goal. This includes maintainability elements and how they relate to others elements such as Reliability, Remanufacturing and other methodologies. Coulter et al. [147] in particular, explain how fasteners contribute to material separation. The information from this thesis can be used as justification for the methodology used for selecting the type and number of fasteners required for the design for maintainability. Shehory et al. [148] explain how previous and existing information should be organised accordingly as this will improve the strength of maintainability. It will help the aircraft mechanic and engineer to perform their duties accordingly and within the allocated time frame. Again, in this research, this type of effort can be used for future development, where all information is gathered and fed into a system and therefore the collective information can be channelled to the appropriate systems.

Which elements of maintainability need to be considered the most? Maintainability elements involve three major stages: Disassembly (Removal), Rectification (Inspection, Reliability), and Assembly (Installation). Each one of these stages requires support from several other factors [130].

At the rectification stage, information such as why the component failed is analysed and rectified in order to have the system operate to the specified requirement. At this stage, the history reliability information is highly important. The information is not only used to analyse the trend of the component's failure, it is also very useful to identify potential design improvements, such as type of materials and processes, as well as the potential to improve methods of failure detection. At the Assembly stage, most of components are assembled together in accordance with the manufacturers or maintenance manual. This stage can be considered as the reverse of the disassembly procedure, as any mistake when matching parts to the wrong components may cause further failure and there could be potential difficulty in detecting the failure.

In conclusion, each stage must be carried out with systematic procedures. The major element involved at each stage is time. Generally, the more time taken to carry out each task will affect the next stages, and so on. Several literatures such as [130; 149; 150] were used to identify standard times for disassembly and assembly.

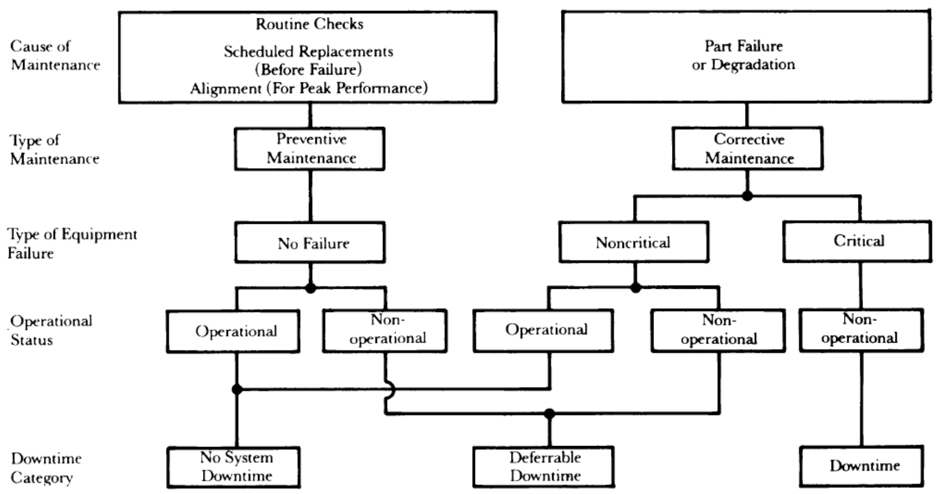


Figure 2—6 Relation of Maintenance and Others Elements [140]

2.6 Summary

After all comprehensive literature reviews have been performed; this section can be summarised as follows:

2.6.1 **Designer Perspective**

At this level, the perspective of maintainability should be improved at the design stage where all required information should be supplied to the respective department such as Engineering or Design. The information supplied should be specific to the problems that have arisen or to the specific required improvements. This is because the designer does not have time to evaluate the whole set of reports from the customer or the end user (i.e. Maintenance Engineer, Mechanic and Pilot). In the aviation industry, there are many feedback mechanisms developed to obtain as much information as possible from the end user in order to improve the existing designed of products or systems. The information is also used to reduce human error, improve the maintenance time interval, and to set a bench mark for the future trend of products or systems to be designed.

2.6.2 **Historical Data and Information Perspective**

To ensure that the improvement of a new design offers additional benefits to those previously provided, historical data should be utilised. Collectively, historical data and information are capable of providing a better understanding for better design improvement and, consequently, be able to offer others benefits such as both cost and human error reductions. There are different types of historical data available from reliable sources.

Based on the literature review, there are more than ten types of reliable sources of information as per described in section 2.4.5 and section 2.4.6. Some sources of information such as Airworthiness Directive (AD) are controlled by regulatory bodies (i.e. FAA and CAA). This research is focused on sources of information that can be used as alternatives to predict maintainability effectiveness. The Service Difficulty Reporting System (SDRS) is the most appropriate source of information that is suitable for this research.

Most of the information included in the SDRS contains information that is useful to the designer when considering improvements such as part conditions, nature of conditions, stage of operations, aircraft types, aircraft model, and precautionary actions. These elements should be able to offer a clear indication to the aircraft designer that the data have been analysed appropriately, accurately and systematically.

In this research, the SDR data were collected from reliable sources and were analysed systematically to ensure the most reported service difficulties are followed by improvement in terms of maintainability prediction.

2.6.3 **Maintenance Perspective**

This level is referred to as the end user of designed products or systems. Almost all the valuable information for future products improvement is supplied from this level. This is because at this level, each person is not only performing his/her duties according to the requirements but they are also putting their ideas or theories of design into a practical form.

2.6.4 **Quantitative Perspective**

After reviewing each element from the MIL-HDBK-472 checklists, the highest score is allocated to the maintenance task needing minimum effort to be performed. Other than that the fewest tools, or no tools, required to perform the maintenance tasks will also be awarded the highest score.

3 Use of Feedback Information for Maintainability prediction

3.1 Objectives

- to illustrate how feedback information can be used to provide information to aid maintainability prediction consequently promote better Design for Maintainability;
- to identify valuable information within Service Difficulty Reporting System (SDRS); and
- to identify potential use of the analysed SDRS for maintainability prediction.

3.2 Overview

One of the reasons why SDR was selected is because the system is comprised of a considerable amount of maintainability related information. The collected data encompass seven information sources: 1) Joint Aircraft/Systems (JASC) Code; 2) Part Name; 3) Aircraft Make; 4) Aircraft Model; 5) Aircraft Systems; 6) Nature Condition; and 7) Stage of Operations. The SDR also contains two categories of data known as “G” category for General Aviation and “A” category for Air Carriers. In this research, the “A” category was used because all the aircraft types and models referring to commercial types of aircraft.

For this research the historical data information for all types of aircraft, JASC Code, aircraft engine types were collected over a period of 10 years, from 2000 until 2009. JASC contains a list of aircraft components and systems which were previously known as the Air Transport Association (ATA) of America [117] and divided into four categories: Aircraft, Airframe Systems, Propeller/Rotor Systems and Powerplant Systems. There are 51 subsystems as shown in Figure 3—1. All are categorised into four different groups namely Aircraft contains 4, Airframe contains 27, Propeller/Rotor Systems contains 6, and Powerplant contains 14.

The process of analyses was implemented by using a Microsoft Excel application. After elements of the JASC Code were identified, the next part of the process was to propose the range of the data set to be selected.

The first step began with data collection and categorisation in accordance with JASC Systems. The purpose of the first step was to validate that the Airframe was the main contributor to SDRS. The second step of the process was to determine the highest contributors to SDRS within the airframe systems. The third steps of the process was to identify the types of part conditions, and was followed by choosing the appropriate aircraft components associated with maintainability and serviceability, and related types of part conditions. The analysis processes were divided into two, namely Global SDR dataset and Detailed SDR dataset analyses. Both analyses are description and results are shown in the following chapter 4.

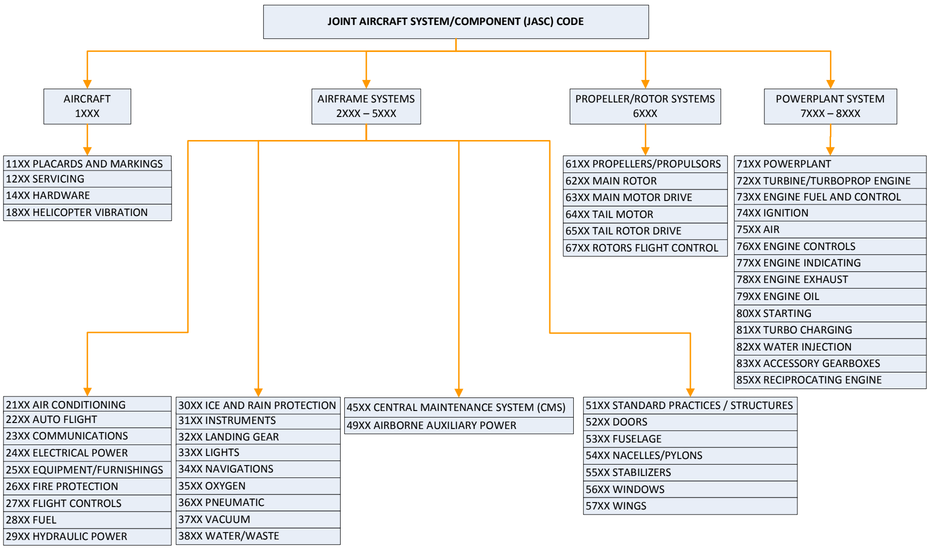


Figure 3—1 Joint Aircraft System/Component (JASC) subsystems

3.3 Proposed process flow for SDR data analysis

This section described, a methodology to analyse the feedback information known as Service Difficulties Report (SDR). Figure 3—2 show the generic process flow for SDR analysis proposed by the author.

The process begins with identifying the data range. In this research, the author decided to use ten years data range starting from year 2000 up to year 2009. This decision is based on authors' own analysis presented in Figure 1—1 and through intensive literature reviews which is previously presented in section 2.4. The following process is using the Joint Aircraft System/Component (JASC) code to identify the problems. This is one of the main reasons the SDRS was selected by author where all the data are arranged in accordance with JASC code. JASC code is previously also known as ATA Chapter.

The following is narrowed the SDR analysis in accordance with systems. In this research, the author was interested in mechanical related components and therefore most of the components are allocated in airframe systems. Other analyses includes the stage of operation where in this analyses the designer is able to known at what stage that most of the service difficulties are discovered and reported.

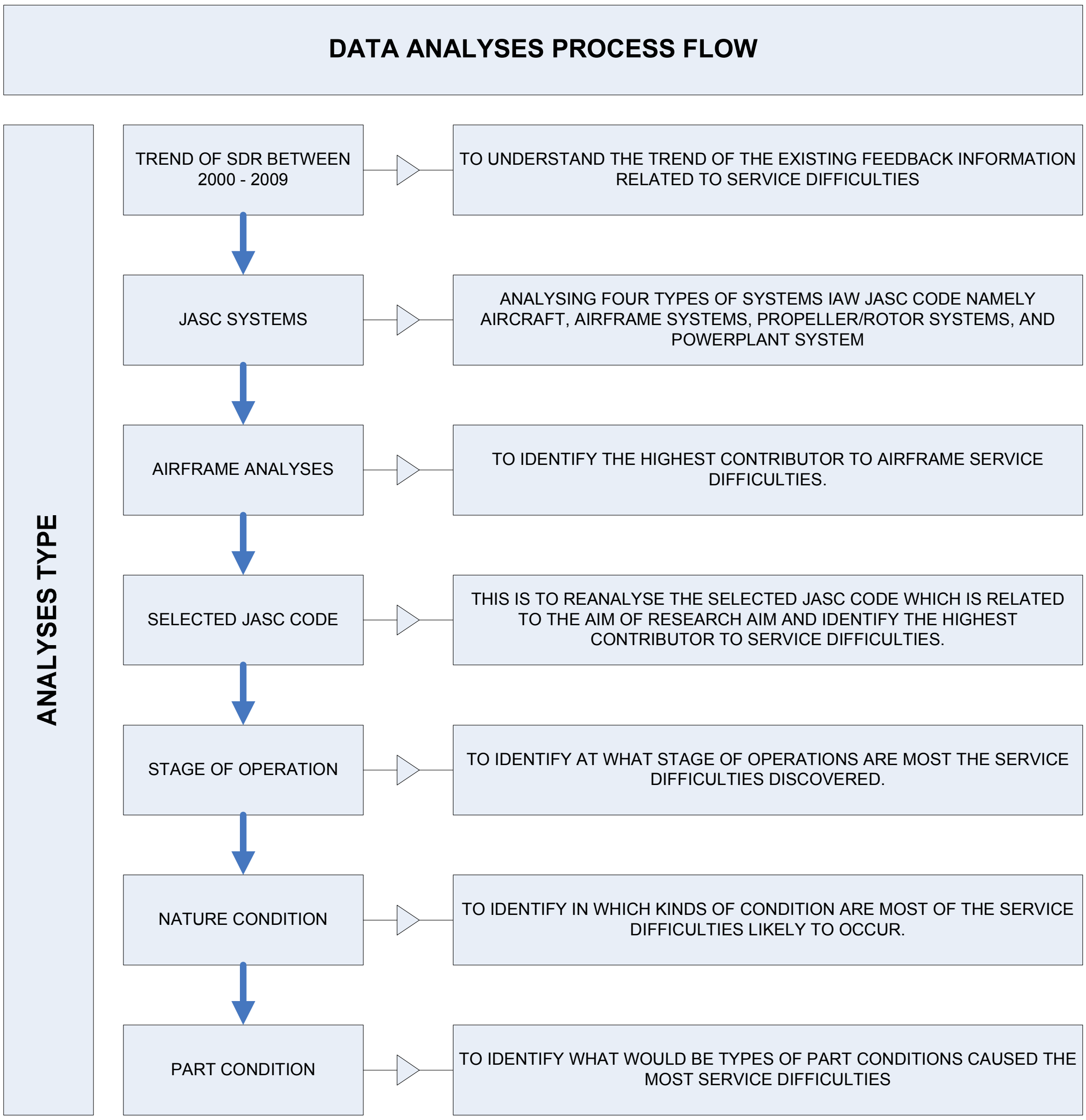


Figure 3—2 Service Difficulties Report generic process flow

Figure 3—3 shows a detailed process flow of SDR data in this research. The process begins with collecting necessary information which was collected for ten years from 2000 to 2009.

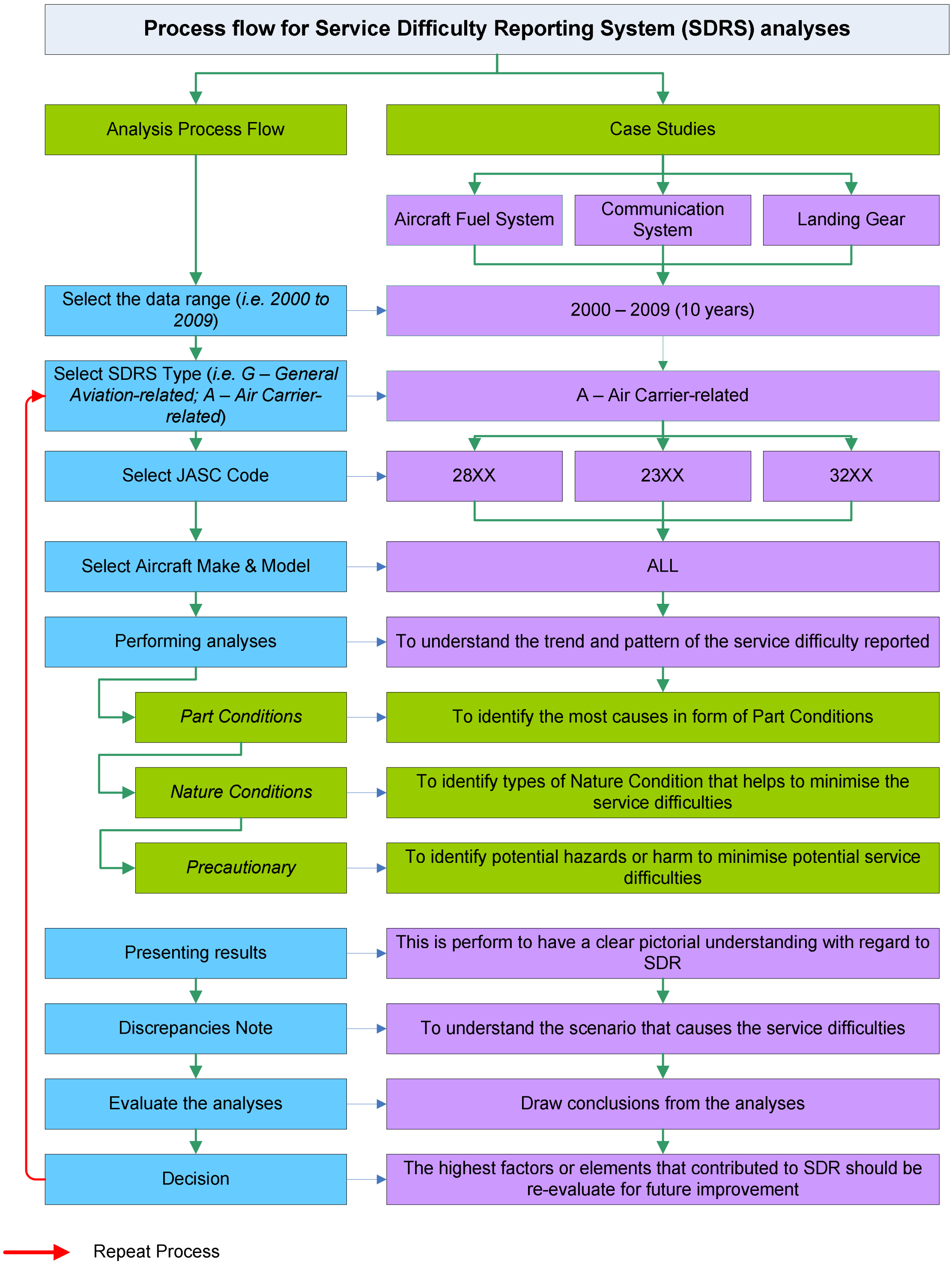


Figure 3—3 Process flow analyses of Service Difficulties Report (SDR)

3.4 Service Difficulties reports (SDR) analyses

3.4.1 **Investigation global analysis of SDR Data**

The results allow identification of the main causes of SDR for all types of aircraft components. The global results as shown in Figure 3—4, that the most common causes of SDR are cracked and corroded condition of parts. This indicates that it is important to select appropriate materials and processes, and analyse the service environment in order to reduce such part condition problems.

However, these types of part condition are difficult to avoid during the design stage. From a design perspective, it is also interesting to consider some of the maintainability related part conditions, such as “inoperative”, “dented” and “damaged”. Feedback from SDR related to these part conditions may be useful to designers of future aircraft in identifying common maintainability problems for the components that they design. Therefore, this thesis suggests that feedback values should be considered as one of the evaluation methodologies used by designers. This is one of the suggestions made in order to aid designers and/or project team members so that such problems are able to be minimised in the future. The detail of global analysis of SDR dataset were presented in Appendix B

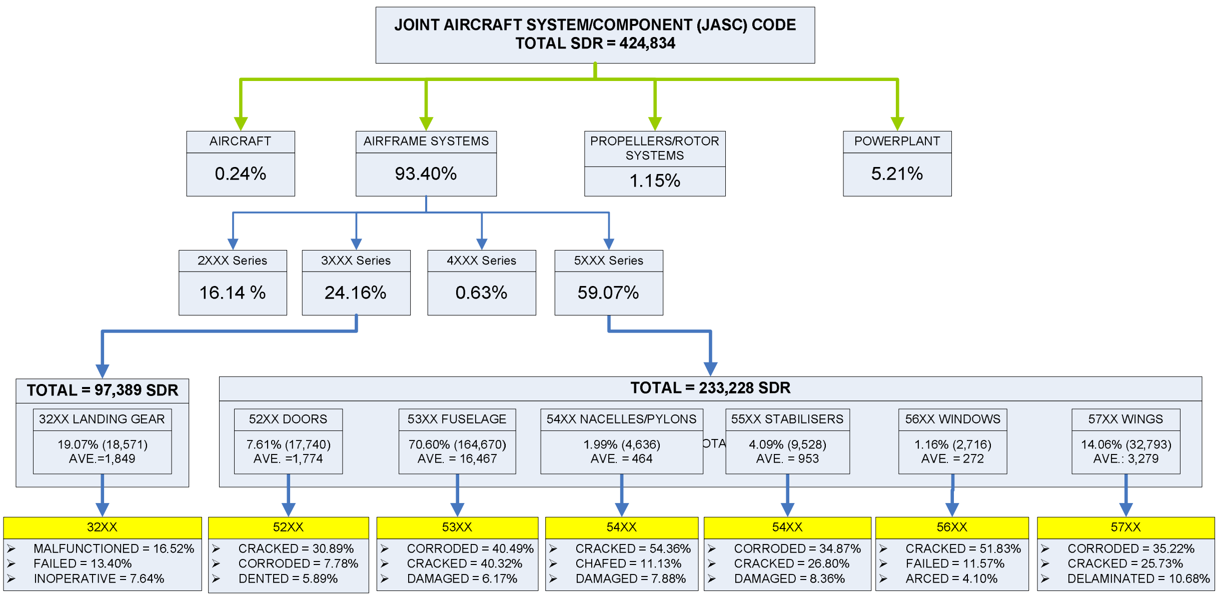


Figure 3—4 Causes of Service Difficulties classified by JASC Code

3.4.2 **Investigation detailed analysis of SDR Data**

The objective of the analysis is to investigate particular components in detail, and particularly to find the information related to maintainability issues. In performing the detailed analysis only a sub-set of part conditions related to maintainability have been analysed. The results show that there are some elements related to maintainability that require attention from the designers. This is because some types of part conditions may cause unnecessary incidents which could be avoided through the improvement of design for maintainability.

Figure 3—5 shows the breakdown of the results for maintainability related SDR. The Landing gear shows the highest percentage of SDR with 44.71% from 3,968 SDRS, followed by fuselage with 25.19% (1,880 SDR), and the third highest is doors with 21.18% (1,880 SDR). Other types of aircraft component such as Nacelles/Pylons, Stabilisers, Windows, and Wings show the values from 1.03% to 5.12% of SDR.

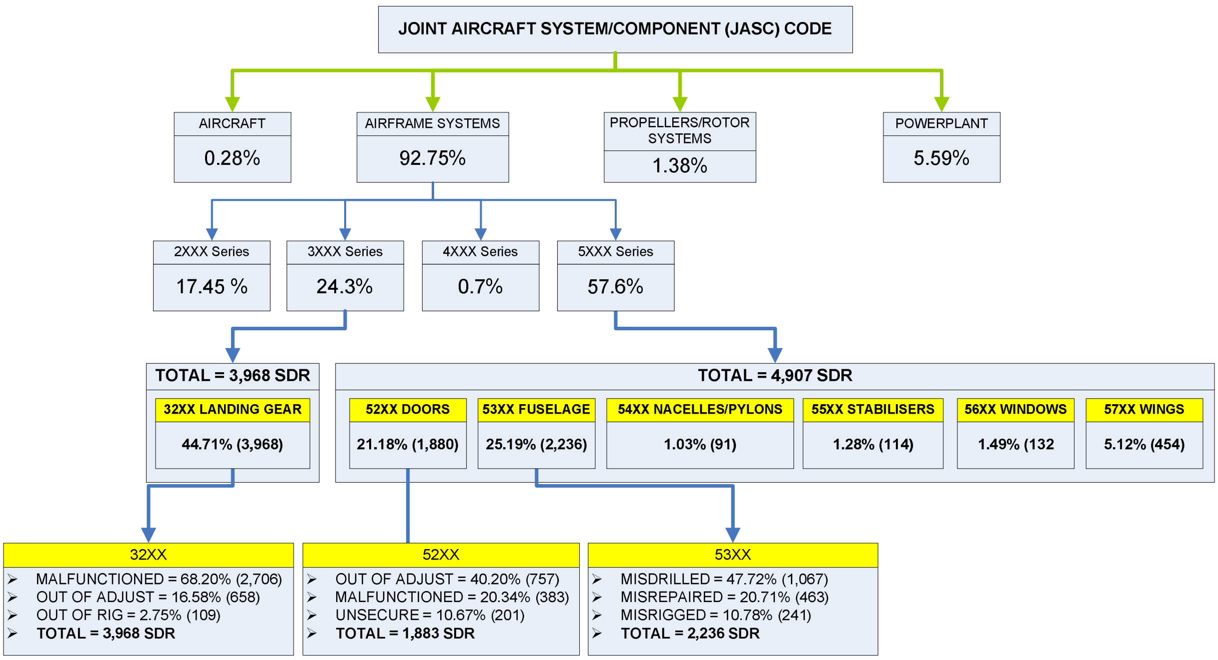


Figure 3—5 Maintainability related causes of Service Difficulties classified by JASC Code

The types of part condition that causes service difficulties vary for different types of aircraft component. For Landing gear, the highest contribution of SDR is from malfunction with 68.20%, followed by out of adjust and out of rig. For doors, the out of adjustment contributed the highest SDR with 40.20% followed by malfunctions and unsecured doors. The fuselage shows that misdrilled contributed the highest SDR with 47.72% compared to other types of part condition such as misrigged.

Based on the results from the first and second analyses, there are two types of indication. The first is that for the whole aircraft system and components, the main issues to be considered are the improvement of cracked and corroded problems. However, these types of part conditions are very difficult to detect or prevent during the design process. Learning from the percentages, the trends and/or the quantity values from the analyses offer opportunities to develop an alternative solution to predict potential failures, such as the cracked and corroded problems. One possible solution is through an improvement in the selection of materials that can extend the aircraft components' lifetime without crack or corrosion, but this may have cost implications.

The second indication is the element of maintainability improvement. There are several maintainability elements that have to be considered in order to evaluate the effectiveness of maintainability. Some of these elements are accessibility, simplicity, serviceability and reliability [53; 64-66; 151]. In addition, the element of time to repair is also included.

In the following sections, detailed analyses of three selected structural components are presented. These have been selected to highlight the different SDR causes for different aircraft component types.

3.4.2.1 Landing Gear detailed analysis

The objective of this section is to illustrate the detailed analysis and results achieved for the Landing Gear. The objective of the analysis is to illustrate the JASC Code most affected by the part conditions. The results are shown in Table 3-1. There are 18, 571 data in total related to Landing Gear in the period 2000 to 2009. The highest contributor to SDR for landing gear is the Landing gear position and warning systems with 25.68% (4,769 SDR), followed by Landing gear retract/extend systems with 17.02% (3,160 SDR).

For part condition malfunctioned contributed 16.5% (3,027 SDR) and failed with 13.4% (2,455 SDR) as shown in Table 3-2. Meanwhile Figure 3—6 depict the percentage distribution for other types of part condition.

Based on the results achieved, it is clear that the electrical elements of aircraft require special attention from the designer, as well as the landing gear retract/extend systems. The potential improvements that could be made from these results are by understanding the elements of mechanical (i.e. hydraulic) and aircraft (i.e. Pilot) handling.

The interest of this research is to find potential solutions for the mechanical aircraft parts. From a maintainability perspective, the elements such as easy access and diagnosis are the main elements to be considered at the design stage. This is to ensure that the malfunctioning and failed components are able to be detected and maintained within the minimum time possible.

Table 3-1 Landing Gear SDR results

NO	JASC CODE	DESCRIPTION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	3200	LANDING GEAR SYSTEM	18	49	39	15	7	6	18	20	21	17	210	1.13%
2	3201	LANDING GEAR/WHEEL FAIRING	3	0	6	1	1	0	0	0	0	0	11	0.06%
3	3210	MAIN LANDING GEAR	41	47	66	81	54	95	84	72	37	25	602	3.24%
4	3211	MAIN LANDING GEAR ATTACH SECTION	64	40	40	28	17	18	22	12	35	52	328	1.77%
5	3212	EMERGENCY FLOTATION SYSTEM	7	1	95	122	17	2	11	5	1	1	262	1.41%
6	3213	MAIN LANDING GEAR STRUT/AXLE/TRUCK	48	42	56	79	42	54	52	69	46	38	526	2.83%
7	3220	NOSE/TAIL LANDING GEAR	88	33	53	49	83	81	59	79	31	34	590	3.18%
8	3221	NOSE/TAIL LANDING GEAR ATTACH SECTION	8	16	10	7	4	1	10	1	3	1	61	0.33%
9	3222	NOSE/TAIL LANDING GEAR STRUT/AXLE	66	83	59	45	23	24	22	58	73	70	523	2.82%
10	3230	LANDING GEAR RETRACT/EXTEND SYSTEM	352	335	385	305	274	282	263	314	357	293	3,160	17.02%
11	3231	LANDING GEAR DOOR RETRACT SYSTEM	70	74	56	45	41	41	52	57	55	70	561	3.02%
12	3232	LANDING GEAR DOOR ACTUATOR	26	37	20	36	13	12	10	15	20	15	204	1.10%
13	3233	LANDING GEAR ACTUATOR	94	63	79	76	70	58	66	83	119	98	806	4.34%
14	3234	LANDING GEAR SELECTOR	83	78	69	66	75	56	59	79	71	67	703	3.79%
15	3240	LANDING GEAR BRAKE SYSTEM	141	75	81	99	132	159	142	245	214	139	1,427	7.68%
16	3241	BRAKE ANTI-SKID SELECTION	36	41	30	42	45	58	52	39	27	42	412	2.22%
17	3242	BRAKE ANTI-SKID SELECTION	148	62	53	44	59	37	41	15	22	25	506	2.72%
18	3243	MASTER CYLINDER/BRAKE VALVE	17	8	17	11	16	22	12	29	23	12	167	0.90%
19	3244	TIRE	48	59	45	47	79	80	78	75	52	57	620	3.34%
20	3245	TIRE TUBE	2	3	3	0	0	1	4	5	6	2	26	0.14%
21	3246	WHEEL/SKI/FLOAT	81	48	96	73	62	59	35	51	50	21	576	3.10%
22	3250	LANDING GEAR STEERING SYSTEM	32	44	45	56	30	70	89	117	53	67	603	3.25%
23	3251	STEERING UNIT	7	7	15	6	10	11	9	6	7	5	83	0.45%
24	3252	SHIMMY DAMPER	0	1	1	0	0	1	3	3	0	0	9	0.05%
25	3260	LANDING GEAR POSITION AND WARNING	513	501	450	548	511	492	405	472	436	441	4,769	25.68%
26	3270	AUXILIARY GEAR (TAIL SKID)	6	4	1	2	3	3	1	2	5	0	27	0.15%
27	3297	LANDING GEAR SYSTEM WARNING	31	39	58	62	54	96	99	145	116	99	799	4.30%
		GRAND TOTAL	2,030	1,790	1,928	1,945	1,722	1,819	1,698	2,068	1,880	1,691	18,571	100.00%

Table 3-2 Landing Gear SDR results in accordance with part conditions (Top 10)

NO	CODE	PART CONDITION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	19	BROKEN	98	86	81	88	49	63	50	53	38	54	660	3.60%
2	39	CORRODED	67	89	122	115	36	50	88	58	69	75	769	4.20%
3	41	CRACKED	242	98	102	74	65	35	40	33	31	25	745	4.07%
4	47	DAMAGED	72	36	64	82	94	64	63	95	69	57	696	3.80%
5	82	FAILED	453	297	279	257	185	210	148	202	224	200	2,455	13.40%
6	86	FAULTY	21	92	120	92	85	88	139	140	130	130	1,037	5.66%
7	120	INOPERATIVE	123	81	85	146	153	175	115	196	163	162	1,399	7.64%
8	127	LEAKING	69	52	79	86	50	49	36	49	42	35	547	2.99%
9	134	MALFUNCTIONED	223	180	251	289	342	347	301	404	383	307	3,027	16.52%
10	164	OUT OF ADJUST	54	94	84	69	67	73	77	72	75	80	745	4.07%
11		OTHERS											6,238	34.05%
												TOTAL	18,318	100.00%

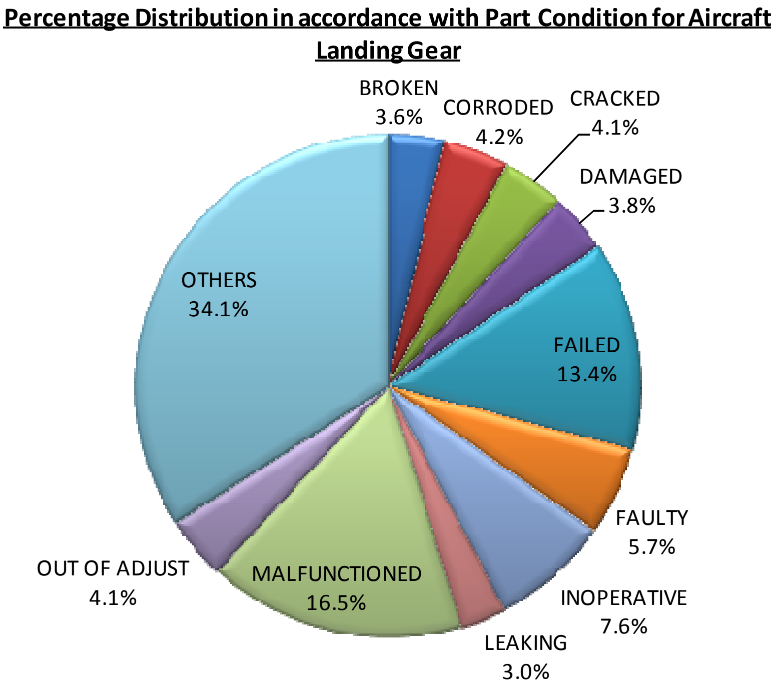


Figure 3—6 Percentage Distribution of Part Condition for the Landing Gear Retraction/Extend System (JASC Code 3230)

3.4.2.2 Door detailed analysis

The second analysis relates to aircraft doors. The objective of the analysis was to identify the dominant JASC Codes for different part conditions. As shown in Table 3-3, the results indicated that the passenger/crew doors contributed the highest SDR compared to others with 40.78% (7,235 SDR) followed by cargo and baggage doors with 23.26% (4,127 SDR).

For the part condition cracked is the highest part condition with 30.89% (5,429 SDR) and followed by corroded with 7.78% (1,368 SDR). All results are shown in Table 3-4 and meanwhile Figure 3—7 depict the percentage distribution of other part conditions for the passenger/crew doors.

Based on these results, the values are as expected because of the role of the doors which are likely to be dented or have mechanical failures. These types of door are most frequently opened and closed. As shown in Table 3-3, the most service difficulties for this type of JASC code are out of adjustment, malfunctioned, and unsecured. The second highest numbers of SDR are contributed by the cargo/baggage doors. Again, this is due to the operation of the doors, which are frequently opened and closed when the aircraft arrives and before departure. This also includes using these doors to gain access to the aircraft for inspection and maintenance activities.

From a maintainability perspective, elements such as accessibility and simplicity are the main factors to be considered at the design stage. Therefore, the time to perform the required diagnosis can be evaluated. This is to ensure that the malfunctioning and failed doors are able to be detected and maintained within the minimum possible time. It is also important to design reliable mechanical systems with robust mechanisms.

Table 3-3 Doors SDR results

NO	JASC CODE	DESCRIPTION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	5200	DOORS	8	31	40	33	11	16	11	24	28	50	252	1.42%
2	5210	PASSENGER/CREW DOORS	520	383	364	401	537	631	787	1,131	1,095	1,386	7,235	40.78%
3	5220	EMERGENCY EXITS	75	58	72	62	55	66	114	153	151	146	952	5.37%
4	5230	CARGO/BAGGAGE DOORS	681	486	407	300	271	376	304	404	427	471	4,127	23.26%
5	5240	SERVICE DOORS	136	118	80	61	67	99	109	130	197	190	1,187	6.69%
6	5241	GALLEY DOORS	9	12	20	9	3	25	29	42	26	17	192	1.08%
7	5242	E/E COMPARTMENT DOORS	32	16	20	5	17	22	36	25	13	34	220	1.24%
8	5243	HYDRAULIC COMPARTMENT DOORS	2	3	3	3	0	1	1	0	1	0	14	0.08%
9	5244	ACCESSORY COMPARTMENT DOORS	11	6	4	2	4	3	4	5	6	8	53	0.30%
10	5245	AIR CONDITIONING COMPARTMENT DOORS	12	1	7	6	11	7	3	7	3	23	80	0.45%
11	5246	FLUID SERVICE DOORS	29	14	4	5	12	8	3	9	10	5	99	0.56%
12	5247	APU DOORS	8	5	10	7	9	2	9	4	6	10	70	0.39%
13	5248	TAIL CONE DOORS	7	2	0	2	4	0	0	1	1	2	19	0.11%
14	5250	FIXED INNER DOORS	9	20	5	29	12	10	13	8	8	7	121	0.68%
15	5260	ENTRANCE STAIRS	48	51	64	117	48	69	133	70	52	45	697	3.93%
16	5270	DOOR WARNING SYSTEM	137	164	190	165	171	137	153	131	148	99	1,495	8.43%
17	5280	LANDING GEAR DOORS	145	92	71	63	78	63	49	104	84	70	819	4.62%
18	5297	DOOR SYSTEM WIRING	4	10	4	7	9	13	13	20	16	12	108	0.61%
		GRAND TOTAL	1,873	1,472	1,365	1,277	1,319	1,548	1,771	2,268	2,272	2,575	17,740	100.00%

Table 3-4 Doors SDR results in accordance with part conditions (Top 10)

NO	CODE	PART CONDITION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	19	BROKEN	30	46	28	43	73	69	61	50	65	51	516	2.94%
2	39	CORRODED	157	112	115	75	81	88	145	184	215	196	1,368	7.78%
3	41	CRACKED	643	477	433	330	355	498	618	789	620	666	5,429	30.89%
4	47	DAMAGED	98	86	56	89	76	89	105	150	181	106	1,036	5.89%
5	54	DENTED	85	71	54	61	51	83	58	59	85	80	687	3.91%
6	105	GOUGED	90	54	38	39	25	48	33	48	51	60	486	2.77%
7	126	LACK OF LUBE	33	29	26	44	47	32	54	99	109	100	573	3.26%
8	132	MAKING METAL	0	0	0	0	0	0	4	14	14	331	363	2.07%
9	134	MALFUNCTIONED	21	25	28	31	24	41	72	60	81	50	433	2.46%
10	164	OUT OF ADJUST	117	93	79	83	65	72	67	83	99	112	870	4.95%
11		OTHERS											5,815	33.08%
												TOTAL	17,576	100.00%

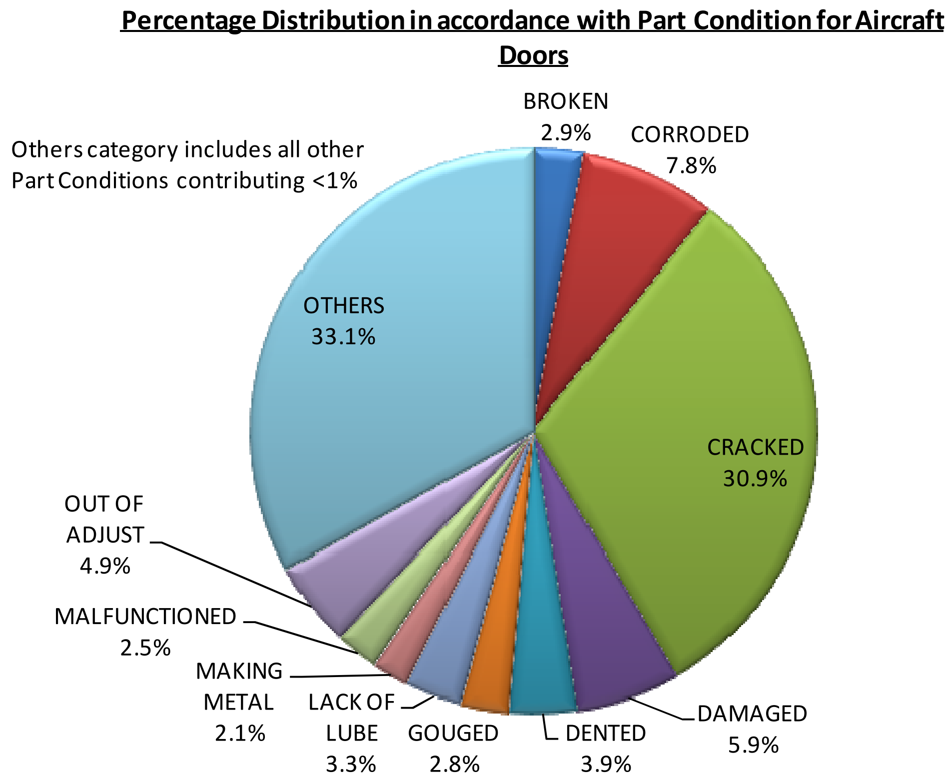


Figure 3—7 Percentage Distribution of Part Condition for the Passenger/Crew Doors (JASC Code 5210)

3.4.2.3 Fuselage detailed analysis

The third case study presents the analysis of the fuselage for the 53XX JASC Code series. The objective of the analysis was to illustrate the JASC Code most affected by the part conditions, and the results are shown in Table 3-5. The JASC Code 53XX series shows that the Fuselage Miscellaneous Structures contributed the highest SDR with 25.11% (41,344 SDR). The second highest is the Fuselage Main, Plates/Skin with 16.12% (20,739 SDR) and the Fuselage Main, Frame contributing the third highest of SDR with 13.46% (17,306 SDR).

For part condition corroded and cracked were the highest part conditions, with each one of them contributing 40.49% (66,573 SDR) and 40.32% (66,305 SDR) respectively. The details of the results are depicted in Figure 3—8.

Table 3-5 Fuselage SDR results

NO	JASC CODE	DESCRIPTION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	5300	FUSELAGE STRUCTURE (GENERAL)	24	679	215	100	26	28	41	39	26	22	1,200	0.73%
2	5301	AERIAL EQUIPMENT	0	0	0	0	0	0	0	0	0	2	2	0.00%
3	5302	ROTORCRAFT TAIL BOM	6	7	24	24	11	4	11	24	29	23	163	0.10%
4	5310	FUSELAGE MAIN, STRUCTURE	1,077	1,772	1,150	854	940	673	1,002	1,006	763	770	10,007	6.08%
5	5311	FUSELAGE MAIN, FRAME	2,378	1,867	1,564	1,050	1,373	1,802	2,281	2,861	3,006	2,728	20,910	12.70%
6	5312	FUSELAGE MAIN, BULKHEAD	731	849	426	387	382	444	424	464	499	736	5,342	3.24%
7	5313	FUSELAGE MAIN, LONGERON/STRAINERS	1,201	966	899	621	782	744	1,019	1,463	833	902	9,430	5.73%
8	5314	FUSELAGE MAIN, KEEL	106	92	103	87	100	110	97	93	98	154	1,040	0.63%
9	5315	FUSELAGE MAIN, FLOOR BEAM	1,702	1,301	1,123	1,015	1,331	1,303	1,414	1,516	1,683	1,563	13,951	8.47%
10	5320	FUSELAGE MISCELLANEOUS STRUCTURE	6,400	4,127	3,584	2,952	3,401	3,303	3,438	3,833	4,508	5,798	41,344	25.11%
11	5321	FUSELAGE FLOOR PANEL	706	353	313	469	547	387	501	338	794	1,196	5,604	3.40%
12	5322	FUSELAGE INTERNAL MOUNT STRUCTURE	13	18	10	10	32	493	502	486	565	698	2,827	1.72%
13	5323	FUSELAGE INTERNAL STAIRS	0	0	1	0	0	3	1	0	1	0	6	0.00%
14	5324	FUSELAGE FIXED PARTITIONS	0	1	2	1	1	1	0	0	0	0	6	0.00%
15	5330	FUSELAGE MAIN, PLATE/SKIN	2,609	2,385	2,121	1,938	2,243	2,610	3,109	2,960	2,833	3,085	25,893	15.72%
16	5340	FUSELAGE MAIN, ATTACH FITTINGS	240	83	85	218	500	1,170	1,315	1,942	1,830	1,668	9,051	5.50%
17	5341	FUSELAGE, WING ATTACH FITTINGS	3	6	6	5	2	3	5	3	5	1	39	0.02%
18	5342	FUSELAGE, STABILIZER ATTACH FITTINGS	19	26	19	12	10	5	6	8	5	11	121	0.07%
19	5343	LANDING GEAR ATTACH FITTINGS	28	32	46	24	54	60	39	85	61	34	463	0.28%
20	5344	FUSELAGE DOOR HINGES	3	7	8	2	1	30	40	24	44	36	195	0.12%
21	5345	FUSELAGE EQUIPMENT ATTACH FITTINGS	9	15	18	11	9	6	8	5	3	24	108	0.07%
22	5346	POWERPLANT ATTACH FITTINGS	0	77	18	13	18	42	29	29	14	5	245	0.15%
23	5347	SEAT/CARGO ATTACH FITTINGS	2,359	1,479	1,280	865	1,221	1,569	2,285	1,779	1,717	1,469	16,023	9.73%
24	5350	AERODYNAMIC FAIRINGS	105	48	33	106	61	39	58	74	80	84	688	0.42%
25	5397	FUSELAGE WIRING	0	0	1	1	2	2	4	1	0	1	12	0.01%
		GRAND TOTAL	19,719	16,190	13,049	10,765	13,047	14,831	17,629	19,033	19,397	21,010	164,670	100.00%

Table 3-6 Fuselage SDR results in accordance with part conditions (Top 10)

NO	CODE	PART CONDITION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	29	CHAFED	227	122	217	187	103	139	181	163	123	128	1,590	0.97%
2	39	CORRODED	7,884	6,598	5,760	4,412	5,631	6,191	7,746	7,158	6,907	8,286	66,573	40.49%
3	41	CRACKED	7,847	6,666	4,874	4,148	4,934	5,716	6,435	8,610	8,538	8,537	66,305	40.32%
4	47	DAMAGED	950	856	628	502	727	760	936	1,123	1,735	1,931	10,148	6.17%
5	53	DELAMINATED	23	84	34	107	132	133	149	61	97	59	879	0.53%
6	54	DENTED	632	698	587	529	673	587	772	732	766	716	6,692	4.07%
7	105	GOUGED	452	332	359	232	209	251	303	259	342	338	3,077	1.87%
8	138	MISDRILLED	595	86	14	1	50	195	118	5	0	0	1,064	0.65%
9	145	MISREPAIRED	32	16	4	11	13	23	103	264	222	333	1,021	0.62%
10	271	WORN	310	156	111	119	124	123	111	128	171	116	1,469	0.89%
11		OTHERS											5,619	3.42%
												TOTAL	164,437	100.00%

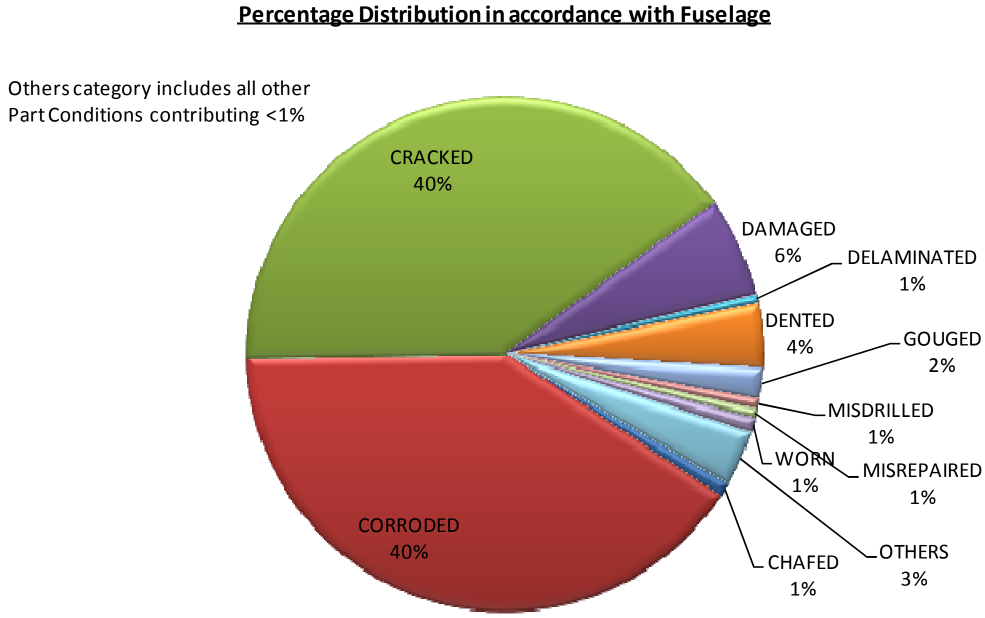


Figure 3—8 Percentage Distribution of Part Condition for the Fuselage Miscellaneous Structures (JASC Code 5320)

The results for the fuselage show significantly different patterns of SDR to those of the landing gear and doors. The fuselage structure does not have any mechanical components so does not suffer from the difficulties of “malfunctioned” or “out of adjustment”. For this component, the fatigue related problems of cracking and corrosion are the major problems for design consideration.

3.4.2.4 Stage of Operations

In this section, the objective of the analysis was to answer the question *When do most of the difficulties happen and/or are discovered?* To answer this question, the collected data set from the 1st analysis of the investigation was used. The analysis was based on a 424,834 data set collected. There are 17 stages of operations, highlighted as depicted in Table 3-7. The results show that an average of 72.68% of part conditions are discovered during inspection and maintenance activities, which demonstrates that current maintenance practices are generally effective in identifying faults.

Table 3-7 SDR Stage of operations analysis

NO	CODE	STAGE OF OPERATIONS	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	AA	AIR AMBULANCE	0	0	0	0	0	1	0	4	11	19	35	0.008%
2	AB	AEROBATIC	1	0	0	0	0	0	0	0	0	0	1	0.000%
3	AG	AGRICULTURE	0	1	2	0	0	0	0	0	0	0	3	0.001%
4	AP	APPROACH	661	700	644	594	666	768	775	901	870	763	7,342	1.728%
5	CL	CLIMB	3,071	2,895	2,776	2,458	2,572	2,671	2,328	2,705	2,618	2,418	26,512	6.241%
6	CR	CRUISE	2,131	2,435	2,239	2,000	1,967	1,919	2,117	2,384	2,093	2,021	21,306	5.015%
7	DE	DESCENT	374	389	414	375	384	422	441	456	414	455	4,124	0.971%
8	EX	EXTERNAL LOAD	1	0	3	0	0	0	0	0	1	0	5	0.001%
9	FF	FIRE FIGHTING	0	0	3	0	0	0	0	0	0	0	3	0.001%
10	HO	HOVERING	6	4	17	4	8	11	2	3	1	3	59	0.014%
11	IN	INSP/MAINT	33,302	29,547	26,253	21,883	25,183	25,428	32,306	36,377	38,092	40,407	308,778	72.682%
12	LD	LANDING	281	273	272	261	265	319	349	404	302	295	3,021	0.711%
13	MS	MAPPING/SURVEY	0	0	0	0	0	0	0	0	0	0	0	0.000%
14	NR	NOT REPORTED	959	1,188	1,146	5,660	3,156	3,130	4,383	2,930	2,630	1,721	26,903	6.333%
15	TO	TAKEOFF	1,150	1,172	1,189	894	1,005	861	1,091	896	644	606	9,508	2.238%
16	TX	TAXI/GRND HDL	1,067	1,255	1,303	1,321	1,343	1,447	1,692	1,804	1,139	1,445	13,816	3.252%
17	UK	UNKNOWN	87	258	334	243	74	81	229	296	505	1,311	3,418	0.805%
													424,834	100%

During the last 10 years, the trend of service difficulties were decreasing, starting in 2001; however, the trend of service difficulties has since increased, starting from 2003, as shown in Figure 3—9. This is possibly happening due to the age of the aircraft. However, further analyses could be performed to investigate the sources of SDR that occur during flight, and whether maintainability prediction could be used to reduce these problems in the future.

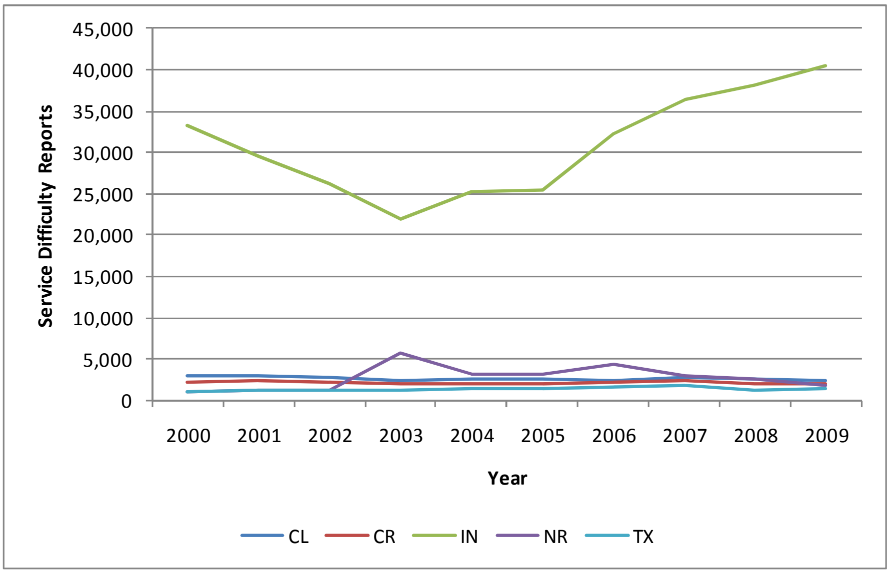


Figure 3—9 The trend of the top five stages of operations

3.4.3 **The evaluation of Service Difficulties Reports (SDR)**

SDR analyses were divided into two phases: Global SDR analysis and Detailed SDR analyses. The former includes all analyses of all Joint Aircraft Component and System (JACS) codes, the latter detailed being the analyses for specific and selected JASC codes related to this research interest.

The following process of SDR is **to identify a methodology to make use of the analysed SDR**. The focus is to answer the question *How should the analysed numbers be used?* In this research, the author proposes to convert the SDR analyses into a rate by using the following formula.

$$Service\ Difficulties\ Rate\ (SR) = \frac{Number\ of\ Service\ Difficulties\ per\ year}{Number\ of\ flight\ Flown\ hours\ per\ year}$$

Equation 3-1

The Service Difficulties Rate is the term proposed and used by author and abbreviated to SR. Equation 3-1 is used as the main formula to be used for the next process to investigate the potential correlation between Failure Rate (λ) and Service Difficulties Rate (SR). The outcome from this research will be able to answer one of the research questions: How can a method to incorporate feedback for a maintainability prediction in the early design process be developed, structured, and efficiently used by the designer? Both the values of failure rate and number of flight flown hours per year have been collected from reliable sources of information known as Non Electronic Product Data (NPRD) [152], and from the Federal Aviation Administration (FAA) [153]. This is to ensure consistencies within the data sets. The FAA numbers of flight flown hours per year are depicted in Appendix C**.**

3.4.4 **Investigation of correlation between Failure Rate (λ) and Service Difficulties Rate (SR)**

All the SDR data sets have been presented in a previous chapter 3. Most of the collected data sets have been converted into a Service Difficulties Rate (SR) by using Equation 3-1. For the purpose of testing, three case studies have been used: Aircraft Fuel System (JASC 28), Aircraft Communications (JASC 23), and Aircraft Landing Gear (JASC 32) because of availability.

The detail SDR Data set for each case study is shown in Appendix D for Aircraft fuel system, Appendix E for Aircraft communications, and Appendix F for Aircraft Landing gear.

The trendline is used to graphically display trends in data and to analyse problems of prediction. As an example, a trendline is shown in Figure 3—10 for Aircraft Fuel Systems, Figure 3—12 for Aircraft Communication Systems and Figure 3—14 for Aircraft Landing Gear. It can be seen that there is a large amount of scatter in the results. The trendline accuracy is measured by a parameter known as the R-squared value, abbreviated to R^2. The value of R^2 is measured between 0 and 1. The trendline is considerably accurate and reliable when the R^2 value is nearly equal or equal to 1. The R^2 value also can be calculated by using the following formula:

$$Y = m X + b$$

Where y = The Service Difficulty Rate; m = slope; X = The Failure Rate (λ); and b = intercept value.

3.5 Testing Correlation between Service Difficulties Rate and Failure Rate

In this section three case studies will be presented to investigate the correlation between Service Difficulties Rate (SR) and Failure Rate (λ)

3.5.1 **Case Study 1 – Aircraft Fuel System**

The first case study is aircraft fuel systems. Table 3-8 shows the list of aircraft fuel system components, list of failure rates and predicted service difficulty rates. The predicted service difficulty rate was abbreviated as SR and calculated using Equation 3-1.

Table 3-8 List of Failure Rate versus Service Difficulties Rate - Aircraft Fuel System

No	Aircraft Components	FR	SR
1	Hand Pump	1.0000E-06	1.5802E-05
2	Reservoir Fill Selection Valve (RFSV)	2.0000E-05	5.4115E-07
3	Pressure Valve (PV)	2.8000E-05	5.4115E-08
4	Reservoir	2.8000E-05	5.4115E-08
5	Non Return Valve (NRV)	1.3000E-07	8.9831E-06
6	Engine Driven Pump (EDP)	2.7000E-05	1.5802E-05
7	Non Return Valve (NRV)	4.8000E-05	8.9831E-06
8	Aircraft Motor Pump (ACMP)	2.7000E-05	1.5802E-05
9	Non Return Valve (NRV)	8.2000E-06	8.9831E-06
10	Pipe	2.7000E-05	2.7057E-07
11	Pump Overheat Light (POL 1)	1.4000E-06	5.4115E-08
12	Pump Overheat Light (POL 2)	7.1100E-05	5.4115E-08
13	Pump Low Light (PLL 1)	7.1100E-05	5.4115E-08
14	Pump Low Light (PLL 2)	6.0500E-04	5.4115E-08
15	Heat Exchanger (HEX)	6.0500E-04	5.4115E-08
16	Hydraulic Low Light (HLL 1)	1.1200E-06	5.4115E-08
17	Hydraulic Low Light (HLL 2)	3.1300E-04	5.4115E-08
18	Hydraulic Low Light (HLL 3)	3.1300E-04	5.4115E-08
19	Hydraulic Quantity Indicator (HQ 1)	3.1300E-04	6.1150E-06
20	Hose	1.5000E-05	1.1364E-06
21	Depressurisation Valve (DPV)	1.1000E-05	8.9831E-06
22	Non Return Valve (NRV)	1.0700E-04	8.9831E-06
23	Moisture Vent Trap (MVT)	2.7000E-05	4.8703E-07

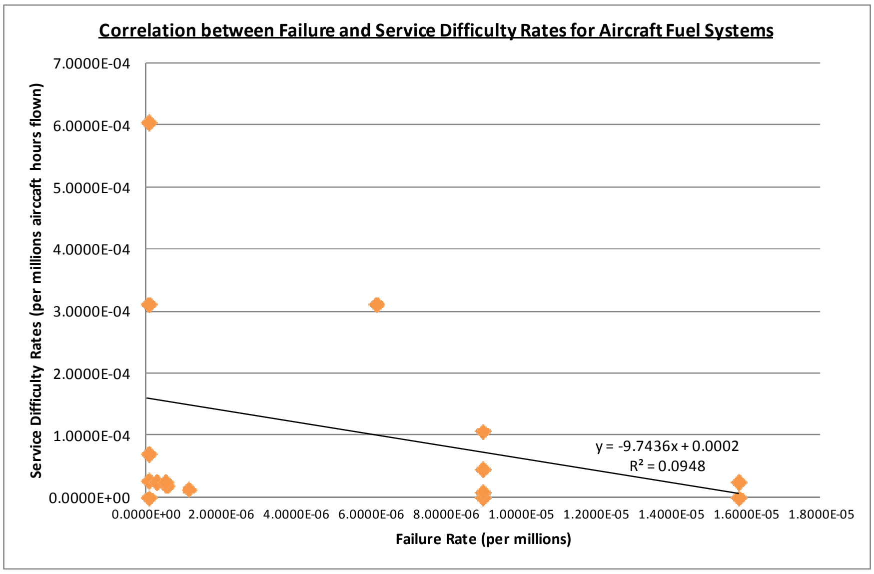
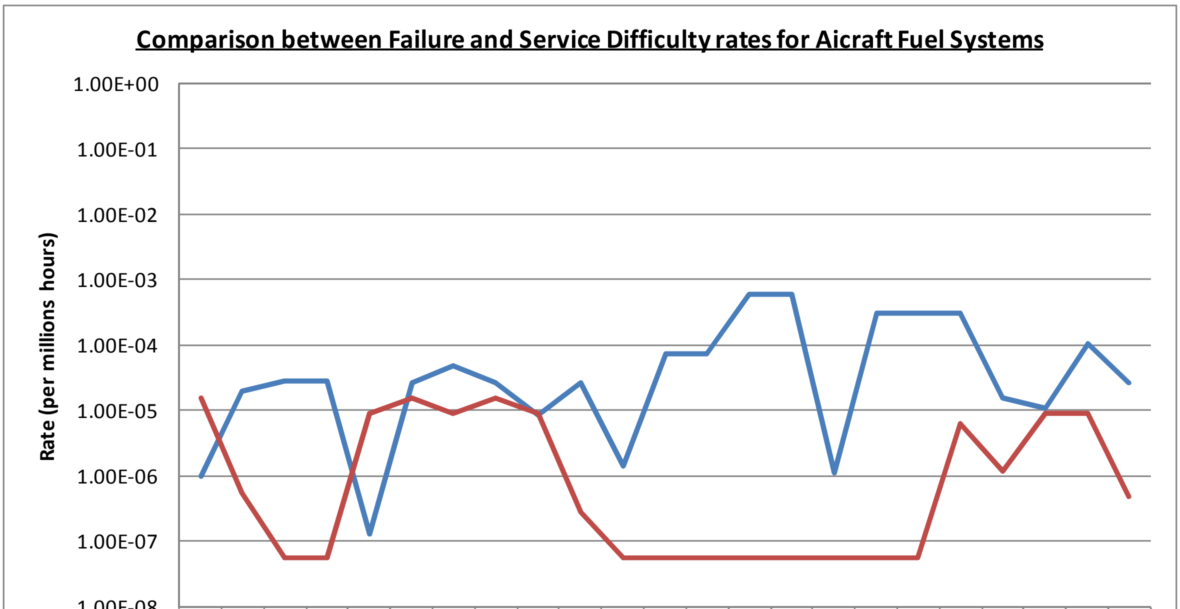


Figure 3—10 Failure Rate versus Service Difficulty Rate for Aircraft Fuel Systems (JASC 28)

Figure 3—11 shows the line patterns between failure rate and service difficulties rate. The line patterns comparison between both lines is not the same and therefore the author concluded there is no correlation between failure and service difficulties rates for aircraft fuel systems (JASC 28) and consistence results, as shown in Figure 3—10.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
FR	1.00	2.00	2.80	2.80	1.30	2.70	4.80	2.70	8.20	2.70	1.40	7.11	7.11	6.05	6.05	1.12	3.13	3.13	3.13	1.50	1.10	1.07	2.70
SR	1.58	5.41	5.41	5.41	8.98	1.58	8.98	1.58	8.98	2.70	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	6.11	1.13	8.98	8.98	4.87

Figure 3—11 Comparison Failure and Service Difficulty Rates for Aircraft Fuel Systems

3.5.2 **Case Study 2 – Aircraft Communications**

Table 3-9 shows the second case study which is for the aircraft communication system [154] (JASC 23). The predicted service difficulty rate was abbreviated as SR and calculated using Equation 3-1.

Table 3-9 List of Failure Rate versus Service Difficulties Rate - Aircraft Communications (JASC 23)

No	System / Sub System	Rate	
		Failure	Difficulties
1	Audio Selector Panel 1	1.66805E-04	1.89402E-06
2	Audio Selector Panel 2	1.66805E-04	1.89402E-06
3	Headset 1	1.56400E-04	7.03495E-07
4	Headset 2	1.56400E-04	7.03495E-07
5	Handheld Microphone 1	3.55700E-04	1.78579E-06
6	Handheld Microphone 2	3.55700E-04	1.78579E-06
7	Speaker 1	4.74600E-05	5.95265E-07
8	Speaker 2	4.74600E-05	5.95265E-07
9	VHF 1 Antenna	1.07580E-05	2.48929E-06
10	VHF 1 Transceiver	6.00000E-05	1.17429E-05
11	VHF 1 Control Panel	1.06596E-04	3.03044E-06
12	VHF 2 Antenna	1.07580E-05	2.48929E-06
13	VHF 2 Transceiver	6.00000E-05	1.17429E-05
14	VHF 2 Control Panel	1.06596E-04	3.03044E-06
15	HF Antenna	3.31000E-05	2.48929E-06
16	HF Lightning Arrestor	2.38140E-05	5.41150E-08
17	HF Antenna Coupler	9.60890E-05	3.13867E-06
18	HF Transceiver	5.83380E-05	1.17429E-05
19	HF Control Panel	1.17750E-05	3.03044E-06
20	Selcal Decoder	2.46745E-05	3.24690E-07
21	Selcal Control Panel	7.23840E-05	3.03044E-06
22	Passenger Address Amplifier 1	1.39992E-04	1.40699E-06
23	Passenger Address Amplifier 2	1.39992E-04	1.40699E-06
24	PA Speaker	4.53200E-05	5.95265E-07
25	PA Speaker	4.53200E-05	5.95265E-07
26	PA Speaker	4.53200E-05	5.95265E-07
27	PA Speaker	4.53200E-05	5.95265E-07
28	Cockpit Voice Recorder Control Panel	2.60000E-05	5.41150E-08
29	Cockpit Voice Recorder	1.50000E-04	5.41150E-08

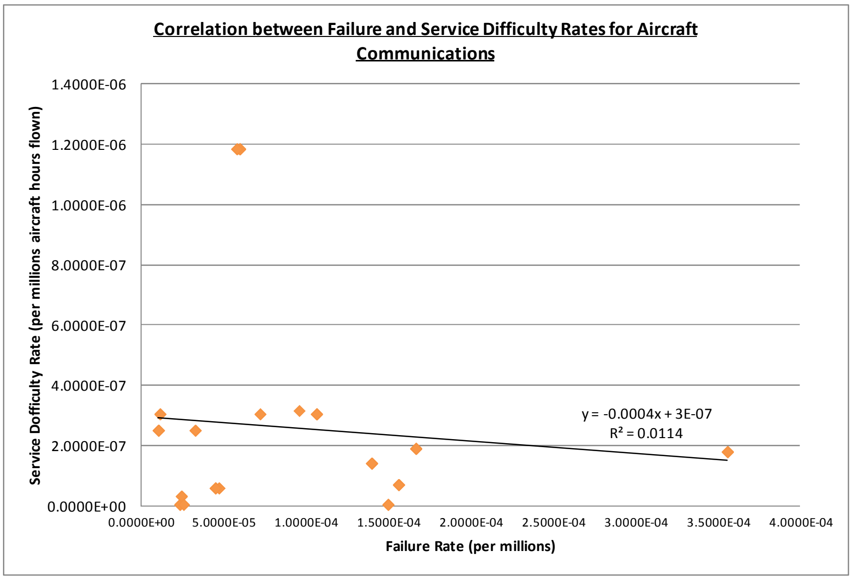
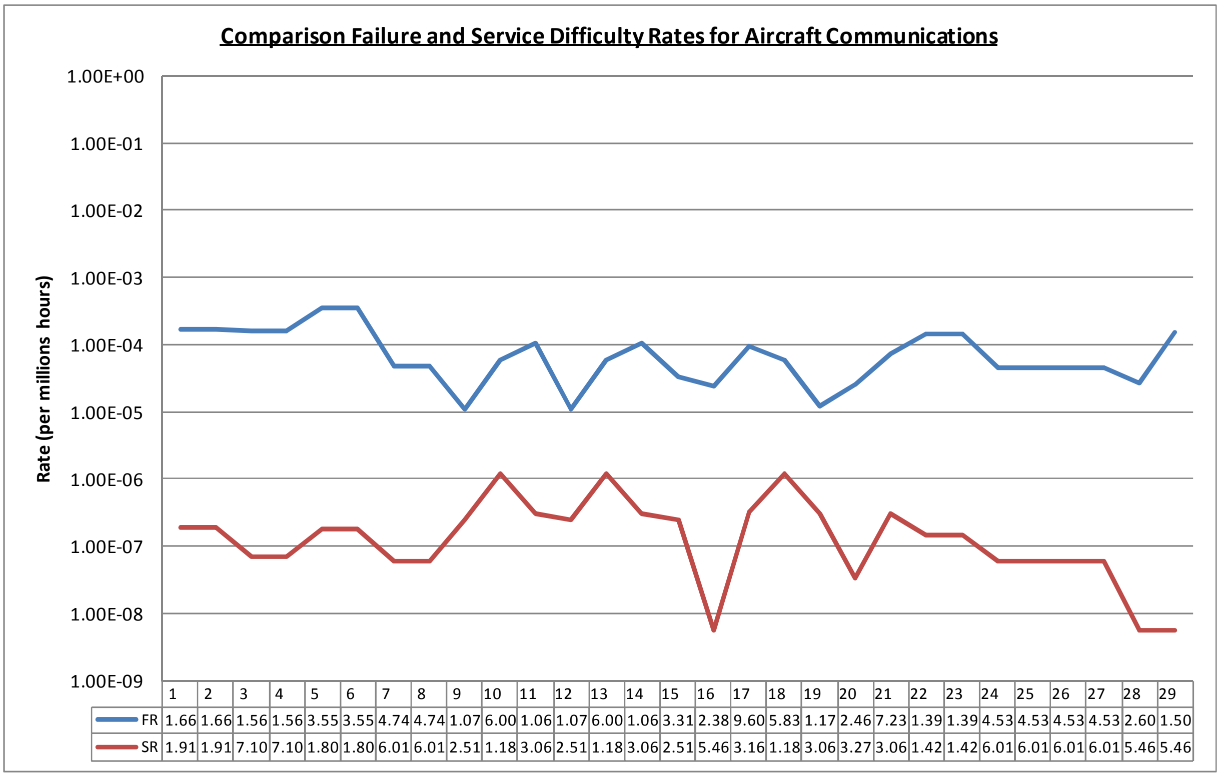


Figure 3—12 Failure Rate versus Service Difficulty Rate for Aircraft Communications (JASC 23)

Figure 3—13 shows the line pattern between failure rate and service difficulties rate for aircraft communication systems. Although the magnitude is significantly different, there is some similarity in the line pattern. The results also show significant error between the patterns and therefore there is no correlation between failure and service difficulties rates for aircraft communications system (JASC 23) and consistence results as shown in Figure 3—12.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
FR	1.66	1.66	1.56	1.56	3.55	3.55	4.74	4.74	1.07	6.00	1.06	1.07	6.00	1.06	3.31	2.38	9.60	5.83	1.17	2.46	7.23	1.39	1.39	4.53	4.53	4.53	4.53	2.60	1.50
SR	1.91	1.91	7.10	7.10	1.80	1.80	6.01	6.01	2.51	1.18	3.06	2.51	1.18	3.06	2.51	5.46	3.16	1.18	3.06	3.27	3.06	1.42	1.42	6.01	6.01	6.01	6.01	5.46	5.46

Figure 3—13 Comparison Failure Rate (FR) and Service Difficulty Rate (SR) for Aircraft Communications

3.5.3 **Case Study 3 – Landing Gear**

The third case study was the aircraft landing gear (JASC 32), as shown in Table 3-10. The predicted service difficulty rate was abbreviated as SR and calculated using Equation 3-1.

Table 3-10 List of Failure Rates and Service Difficulties Rates - Aircraft Landing Gear (JASC 32)

No	AIRCRAFT COMPONENTS	FR	SR
1	ACTUATOR	1.3684E-04	4.9623E-05
2	BRAKE	6.3609E-04	2.6192E-05
3	BRAKE ASSY	2.1000E-06	2.2566E-05
4	CONNECTOR	4.1056E-05	2.1375E-05
5	CONTROL UNIT	2.3552E-04	1.6343E-05
6	PROXIMITY SENSOR	6.7237E-04	2.8627E-05
7	PROXIMITY SWITCH	1.1625E-04	2.5759E-05
8	SELECTOR VALVE	9.5238E-05	2.3756E-05
9	SENSOR	6.9634E-06	2.1105E-05
10	STRUT	6.6270E-06	2.9222E-05
11	SWITCH	1.1625E-04	3.1116E-05
12	TIRE	1.4960E-05	3.4796E-05
13	UPLOCK SWITCH	6.7017E-05	1.3475E-05
14	V-BELT	1.6401E-04	1.6451E-05
15	WARNING LIGHT	3.2492E-05	2.2404E-05
16	WARNING SYSTEM	2.0442E-05	1.6018E-05
17	WHEEL	3.2361E-06	1.9048E-05
18	WIRE	5.0900E-07	1.5964E-05
19	WIRE HARNESS	2.2727E-06	1.4070E-05

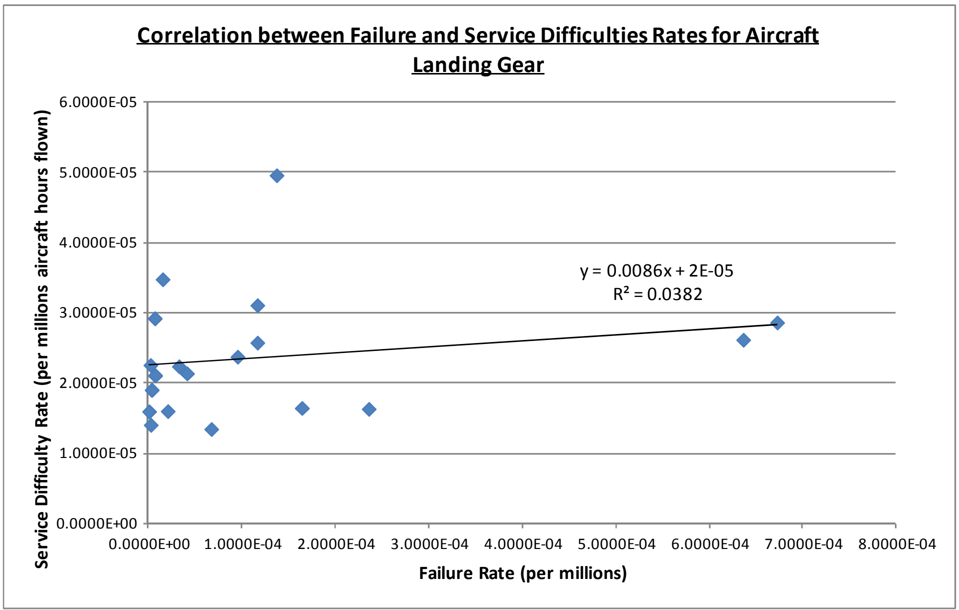
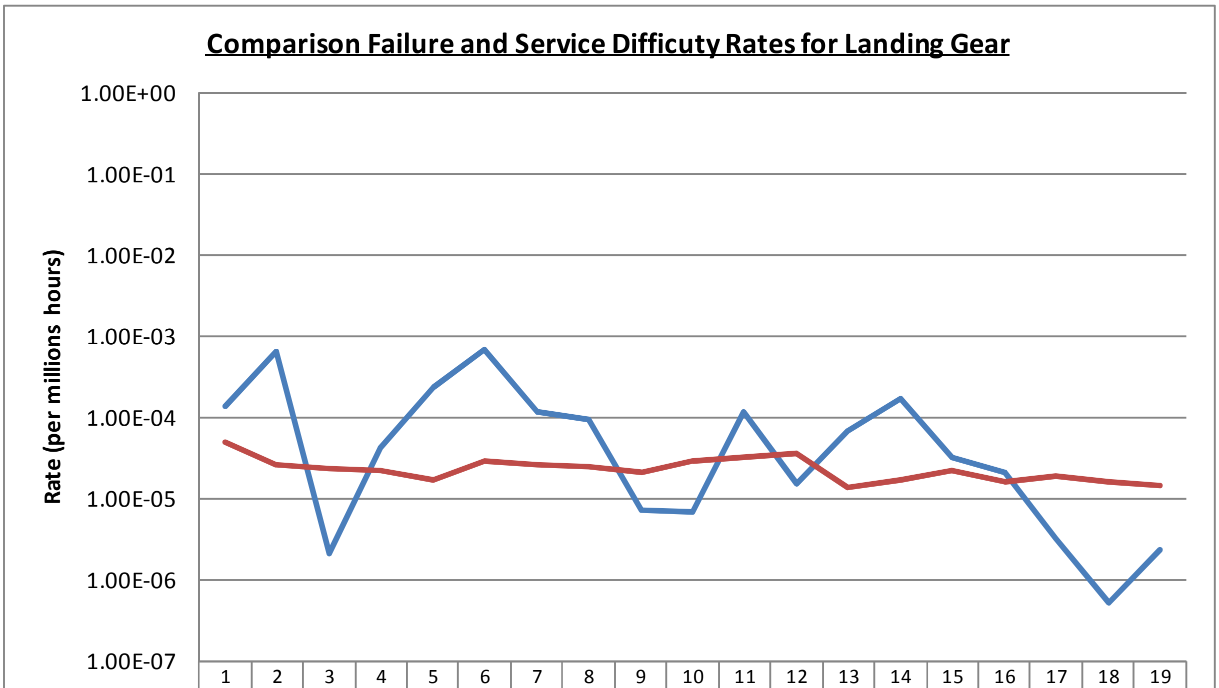


Figure 3—14 Failure Rate versus Service Difficulty Rate for Aircraft Landing Gear (JASC 32)

Figure 3—15 shows the line pattern between failure rate and service difficulties rate for Aircraft Landing Gear (JASC 32). The line patterns for service difficulties rate (SR) shows consistency patterns compared to Failure Rate (λ) as well as inconsistent errors for all components. This outcome shows consistent result, as shown in Figure 3—14 and therefore no correlation between failure and service difficulties rates for aircraft landing gear (JASC 32).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
FR	1.368	6.360	2.100	4.105	2.355	6.723	1.162	9.523	6.963	6.627	1.162	1.496	6.701	1.640	3.249	2.044	3.236	5.090	2.272
SR	4.962	2.619	2.256	2.137	1.634	2.862	2.575	2.375	2.110	2.922	3.111	3.479	1.347	1.645	2.240	1.601	1.904	1.596	1.407

Figure 3—15 Comparison Failure and Service Difficulty Rates for Aircraft Landing Gear

Overall, based on the testing by using three different case studies in this section, the author has concluded that the analysed SDR is not able to be used as an alternative to the failure rate. This is because, as shown in the results above, there is no correlation between failure and service difficulty rates. One of the main issues identified by the author is that some of the aircraft components and/or systems have no reported service difficulties for the whole ten years period under review. However, there are some components and/or systems that have less than ten service difficulties reports. Therefore, these issues make it difficult for this research to identify potential improvement.

3.6 Summary

Although, there are no correlations from all case studies, do not show any correlation between Service Difficulties Rate and Failure Rate, however, the SDR analysis does provide important feedback information has abilities to contribute an important role in design activities. The SDR can be utilised effectively not only for design modification but also for future design improvement by providing and presenting to the designers the simplification and/or summary reports affected the service difficulties as shown in Figure 3—6, Figure 3—7, and Figure 3—8.

4 Maintainability Allocation Methodology

Maintainability Allocation is a process to identify the allowable maximum task time for each individual component. Consequently, this provides clear pictures to the designers to design and identify potential design improvement within allowable maintenance allocation time limits.

The rationale of the development of a maintainability allocation method led to the expansion of an existing maintainability allocation methodology through inserting several new modules and new score values to allocate task times specifically for mechanical aircraft components. The existing maintainability allocation was mostly focused on electrical and electronic systems and components. The maintainability allocation offers the following functions:

1. Allows the maximum allowable task times to be predicted; and
2. Acts as a task time bench mark (if there is no actual time available).

4.1 Objectives

- to extend an existing maintainability allocation methodology for use with mechanical components; and
- to calculate the maximum allocation time for maintenance tasks for each individual aircraft component for use early in design process. This will provide a target maintenance time for each individual component which the designer can use when designing components.

4.2 Chipchak's method

Chipchak's [14] methods consists of three main weighting factors namely Generic Modules Types (Kj1), Fault Isolation Techniques (Kj2), and Differences in M Design Characteristic (Kj3). M is referring to modules. In Table 4-1 depicts the existing list of modules and score values. In total there 13 modules but only three modules, namely numbers 11, 12 & 13, are closely related to mechanical aircraft components. Based on this scenario and because the nature of this research is focused on mechanical aircraft components, the author decided to extend the method for other applications to mechanical components

Towards the end of the section, the proposed modules and score values will be used to predict maintainability allocation for mechanical components. The rationale is to identify the maximum maintenance task time for each individual component while the maintainability prediction is carried out. Others modules includes Fault Isolation Techniques or Kj2 which presented in Table 4-2 and Differences in M Design Characteristic or Kj3 which presented in Table 4-3.

Table 4-1 Existing list of Modules and Score values in Chipchak's method [14]

EXISTING MODULE AND SCORE		
No	Module	Score
1	Lights	1
2	Digital	1
3	Low-level analogue	1.5
4	High-level analogue	1.5
5	Digital Computers	2
6	Power Supplies	2
7	Electromechanical equipment	3
8	High-power/high-frequency components	4
9	Interconnections	4
10	Air conditioners	4
11	Liquid coolant systems	4
12	Mechanical Structures	6
13	Rotating mechanism/engines	10

Table 4-2 Weight Factor Kj2 by Fault Isolation Techniques[14]

Fault Isolation Technique	Kj2	Considerations
Automatic	0	computer or bit circuitry providing automatic fault isolation to replaceable item
Semiautomatic	2	bit circuitry controlled manually (includes test point selector switch/meter combination)
Manual	4	manually making measurements using portable test equipment at circuit test points

Table 4-3 Weight Factor Kj3 by M Design Characteristic[14]

M Design Characteristic	Kj3	Characteristic	
		Accessibility	Handling
Accessibility/Handling			
Simple	0	affords direct access, rack mounted	one-man lift and carry
Difficult	2	involves removal of more than one cover	two-man lift, awkward carry
Very Difficult	4	requires considerable disassembly to reach	hoist lift, needs dolly for movement subject item

4.3 Proposed improvement

4.3.1 Introduction

The prediction of maintenance time in this research consists of two methods: 1) Using the failure rate (λ), and 2) using the service difficulties rate (SR). The purpose of doing this is to compare the results as well as to answer the research question: **How can a method to incorporate feedback for maintainability prediction in the early design process be developed and efficiently used by the designer?** The calculation of allocated maintenance tasks also includes two other elements: 1) Name of Systems/Subsystems and 2) Maintainability prediction[13] procedure III. The following Equation 4-1 and Equation 4-2 are used to calculate the allocation maintenance time. The detailed sequential formula is presented in Appendix G.

$$k = \frac{\sum_{j=1}^{n} \lambda jkj}{\Sigma\, \lambda}$$ **Equation 4-1**

ksystem = Weighting factor for the system
k_j = Individual Weighting factor
λ = Failure Rate

$$R_{pj} = \frac{MTTR}{ksystem} k_j$$ **Equation 4-2**

R_{pj} = Allocated Active Repair Time
MTTR = Mean Time To Repair

4.3.2 Proposed Maintainability Allocation improvement process

The first step in this analysis was to try to find a correlation between allocation maintainability score values used by Chipchak [14] and other measures. Once this relationship had been established, the score values could be calculated for new module types and added to the list of allocation methods.

The development of methodology begins with identifying a methodology for assigning scores values by using the existing list, as shown in Table 4-4. The first approach was to use the failure rate and the results are shown in Figure 4—1. The values of the failure rate are collected by using an NPRD data set [155]. Results show a trend of failure rates that are not consistent with the score values.

Table 4-4 Identifying score value methodology – Approach 1

No	Module[14]	Score[14]	λ (per millions) [154]
1	Lights	1	7.2623E-05
2	Digital	1	2.0440E-05
3	Low-level analogue	1.5	6.0000E-06
4	High-level analogue	1.5	6.0000E-06
5	Digital Computers	2	1.5525E-05
6	Power Supplies	2	1.5525E-05
7	Electromechanical equipment	3	3.0000E-06
8	High-power/high-frequency components	4	2.7364E-05
9	Interconnections	4	5.2304E-05
10	Air conditioners	4	5.0820E-04
11	Liquid coolant systems	4	6.5725E-04
12	Mechanical Structures	6	1.6000E-08
13	Rotating mechanism/engines	10	1.7543E-04

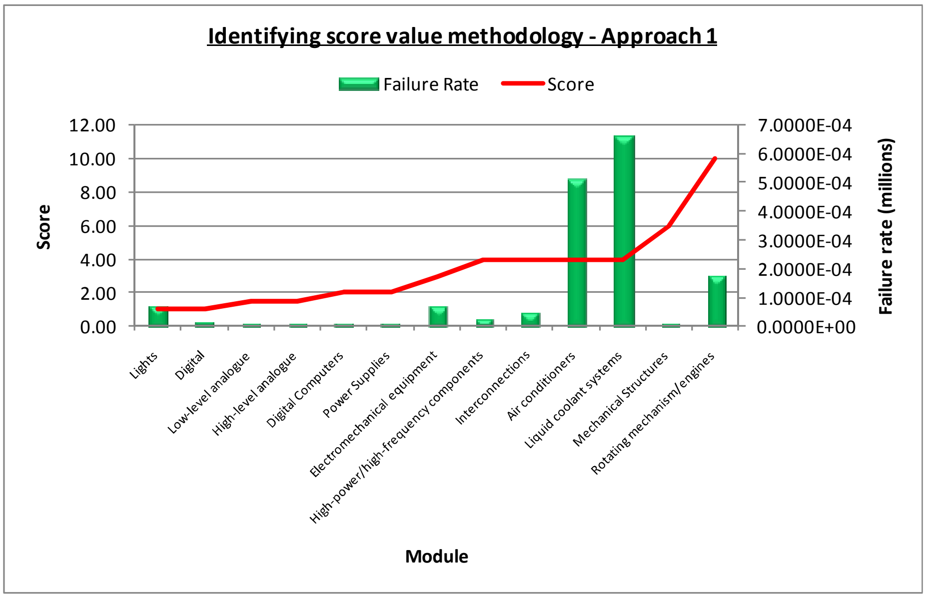


Figure 4—1 The trend of failure rates [155]

A second attempt made was using the task time approach. All the task time values were predicted by using MIL-HDBK-472, Procedure III. The author performed maintenance task time estimation for the removal and reassembly of each component by using the MIL-HDBK-472, Procedure III maintainability prediction method. The outcomes of the estimation are shown in Table 4-5. The outcomes have shown some good indications compared to the first approach. By looking at the minutes or hour values as shown in Figure 4**—2**, the results show consistent values compared to the existing score values. As the task times increased, the score values also increased.

Table 4-5 Identifying score values methodology – Approach 2

No	Module [14]	Minutes	Hour	Score [14]
1	Lights	8.86	0.15	1
2	Digital	31.89	0.53	1
3	Low-level analogue	31.89	0.53	1.5
4	High-level analogue	31.89	0.53	1.5
5	Digital Computers	22.66	0.38	2
6	Power Supplies	20.18	0.34	2
7	Electromechanical equipment	64.45	1.07	3
8	High-power/high-frequency components	48.64	0.81	4
9	Interconnections	40.61	0.68	4
10	Air conditioners	60.41	1.01	4
11	Liquid coolant systems	67.82	1.13	4
12	Mechanical Structures	79.20	1.32	6
13	Rotating mechanism/engines	368.84	6.15	10

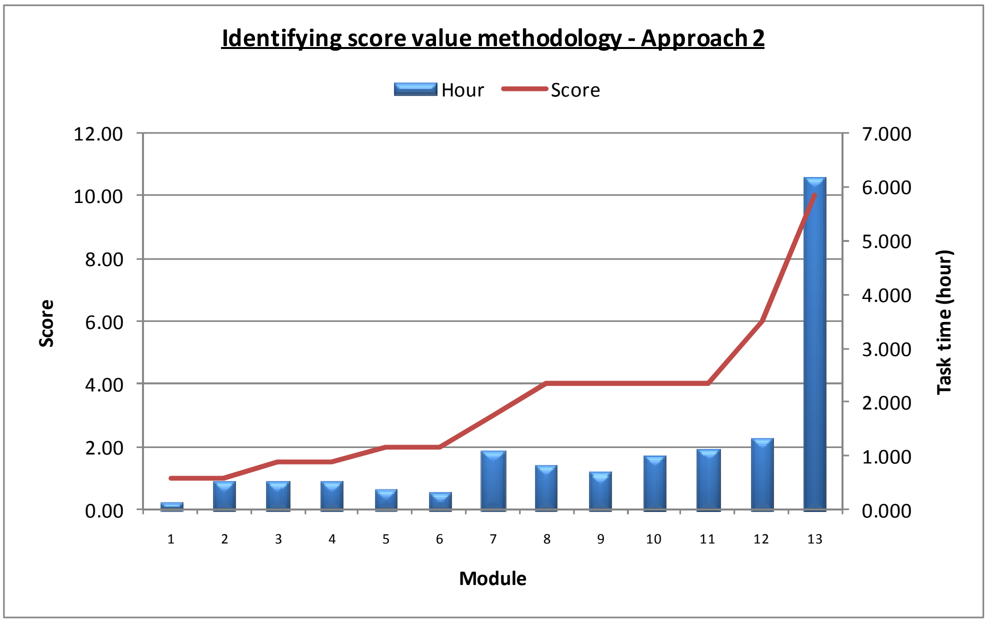


Figure 4—2 Identifying score value methodology – Approach 2

Once the general correlation had been established the following trendlines were performed to identify the most appropriate formula to allow score values to be predicted from any given task time. To do this, the author proposed four different formulae and identified the formulae which have the closest R^2 values. As a result, Figure 4—**3** and Table 4-6 show a summary of the evaluations.

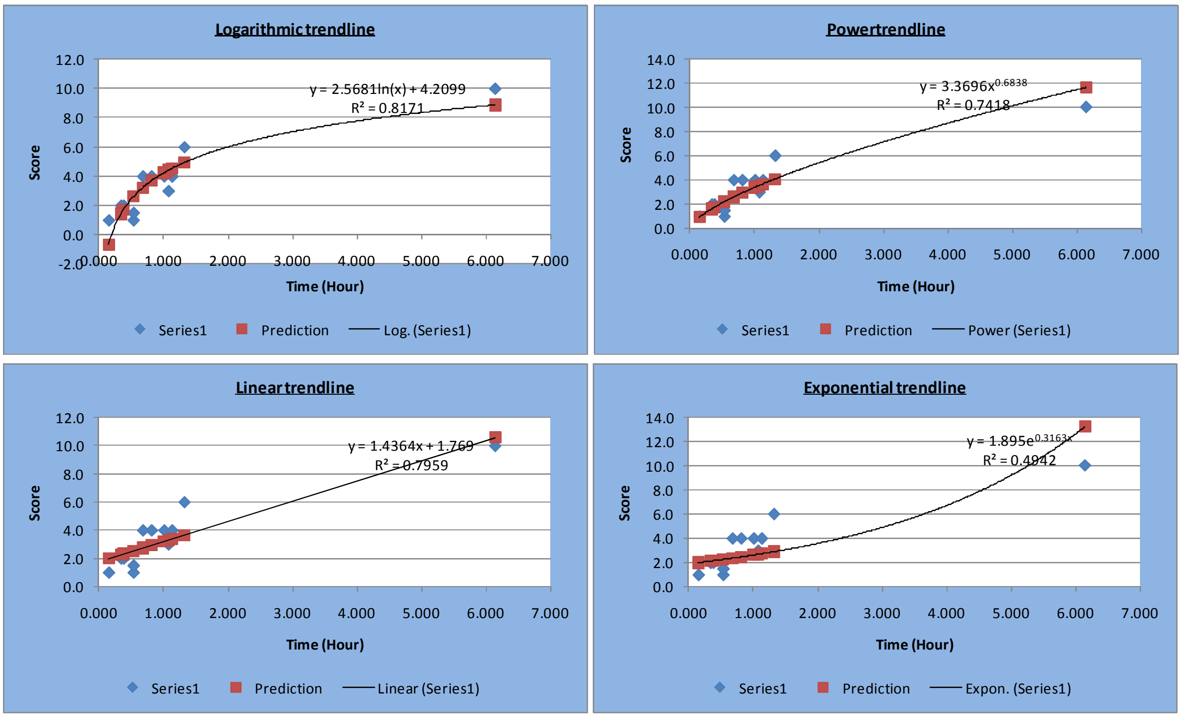


Figure 4—3 Four types for trendlines and formula

Table 4-6 Summary of four types of trendlines and formula

Trendline	**Formula**	**R^2**
Log	$y = 2.5681\ln(x) + 4.2099$	0.8171
Linear	$y = 1.4364x + 1.769$	0.7959
Power	$y = 3.3696x^{0.6838}$	0.7418
Exponential	$y = 1.895e^{0.3163x}$	0.4942

From this initial analysis it can be seen that the Log and Linear trendlines provide the best R^2 values. The selection is based on the closest R^2 value to 1. The results are quite similar so both Log and Linear have been tested. The following process was to apply the selected formula and perform testing and validation. This is to ensure the selected formulae are proven as well as applicable for this research. The testing and validation were performed by using three main case studies: 1) Aircraft Fuel System (JASC 28), 2) Aircraft Communications System (JASC 23), and 3) Aircraft Landing Gear (JASC 32). The testing and validation was performed by using predicted score values, as shown in Table 4-7. The “value” column shows the predicted values means while the “Round” column shows the round from the decimal. In this technique the author decided to use only the 0.5 decimals. Therefore if the predicted value was 2.8 the “round” column result will be 3.0.

Table 4-7 Three types of formula used for testing and validation

No	Generic Module	λ [154] (per millions)	TASKS TIME		SCORE				
			MINUTE	HOUR	EXISTING	LOG FORMULA		LINEAR FORMULA	
						Value	Round	Value	Round
1	Lights	72.6227	8.9	0.15	1.0	-0.7	-1.0	2.0	2.0
2	Digital	20.4399	31.9	0.53	1.0	2.6	3.0	2.5	3.0
3	Low-level analogue	6.0000	31.9	0.53	1.5	2.6	3.0	2.5	3.0
4	High-level analogue	6.0000	31.9	0.53	1.5	2.6	3.0	2.5	3.0
5	Communication	305.9465	23.3	0.39	2.0	1.8	2.0	2.3	2.0
6	Digital Computers	15.5250	22.7	0.38	2.0	1.7	2.0	2.3	2.0
7	Power Supplies	15.5250	20.2	0.34	2.0	1.4	1.0	2.3	2.0
8	Electromechanical equipment	71.1744	64.4	1.07	3.0	4.4	4.0	3.3	3.0
9	High-power/high-frequency components	27.3640	48.6	0.81	4.0	3.7	4.0	2.9	3.0
10	Interconnections	52.3040	40.6	0.68	4.0	3.2	3.0	2.7	3.0
11	Air conditioners	508.1964	60.4	1.01	4.0	4.2	4.0	3.2	3.0
12	Liquid coolant systems	657.2513	67.8	1.13	4.0	4.5	5.0	3.4	3.0
13	Mechanical Structures	0.0160	79.2	1.32	6.0	4.9	5.0	3.7	4.0
14	Mechanical Structures with Mechanism (i.e.: LG, Stabilisers, Wings)	1.0000	217.5	3.63	8.0	7.5	8.0	7.0	7.0
15	Rotating mechanism/engines	175.4275	368.8	6.15	10.0	8.9	9.0	10.6	11.0

4.4 Other elements in maintainability allocation methodology

The following equations are used to predict the maintainability allocation [11].

$$Failure\ Rate\ (\lambda) = \frac{Number\ of\ failures}{total\ operating\ time}$$ **Equation 4-3**

$$Mean\ Time\ Between\ Failure\ (MTBF) = \frac{1}{\lambda}$$ **Equation 4-4**

$$Inherent\ Availability\ (Ai) = \frac{MTBF}{MTBF + MTTR}$$ **Equation 4-5**

$$Mean\ Time\ To\ Repair\ (MTTR) = \frac{MTBF\ (1 - Ai)}{Ai}$$ **Equation 4-6**

In this research, for some of the elements such as MTBF and Inherent Availability (Ai), the author will only assume the values. This is because the author is only interested in and focusing on maintainability prediction and at the same time identifying the appropriate value for MTTR which will be used in maintainability allocation prediction.

For the purpose of illustration, it is assumed that the landing gear systems must be designed to meet an inherent availability (A_i) requirement of 0.9998, an MTBF of 500 hours. Thus, the MTTR requirement is 0.1 hour as shown in calculation below.

$$MTTR = \frac{500\ (1 - 0.9998)}{0.9998} = 0.1$$

4.5 Testing and Case Studies

Testing by using case studies has been carried out. Table 4-8 shows the comparison between two selected formulas (i.e.: LOG and LINEAR). In the existing column, the calculation was performed by using existing score value developed by Chipchak[14]. In LOG and LINEAR columns the calculation were performed by using equation as shown in Table 4-6. Based on the results as illustrated in Figure 4—4 show that the LOG formula is the most suitable formula. This is because the average values indicate the lowest compare value calculated by using LINEAR formula.

Table 4-8 Validation results summary for Aircraft Communication Systems

No	Components [154]	Generic Module Types	Allocation Value (Hour)									Absolute Error (e_i)	
			Existing [154]	x - mean	(x - mean)^2	LOG	x - mean	(x - mean)^2	LINEAR	x - mean	(x - mean)^2	LOG	LINEAR
1	Audio Selector Panel 1	High-level analogue	0.72	-0.29	0.09	1.32	0.34	0.12	1.47	0.54	0.29	0.60	0.75
2	Audio Selector Panel 2	High-level analogue	0.84	-0.17	0.03	1.10	0.12	0.01	1.22	0.30	0.09	0.26	0.38
3	Headset 1	Communication	0.96	-0.05	0.00	0.88	-0.10	0.01	0.98	0.05	0.00	0.08	0.02
4	Headset 2	Communication	0.96	-0.05	0.00	0.88	-0.10	0.01	0.98	0.05	0.00	0.08	0.02
5	Handheld Microphone 1	Communication	0.96	-0.05	0.00	0.88	-0.10	0.01	0.98	0.05	0.00	0.08	0.02
6	Handheld Microphone 2	Communication	0.96	-0.05	0.00	0.88	-0.10	0.01	0.98	0.05	0.00	0.08	0.02
7	Speaker 1	Communication	0.96	-0.05	0.00	0.88	-0.10	0.01	0.98	0.05	0.00	0.08	0.02
8	Speaker 2	Communication	1.44	0.43	0.18	1.32	0.34	0.12	1.22	0.30	0.09	0.12	0.22
9	VHF 1 Antenna	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
10	VHF 1 Transceiver	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
11	VHF 1 Control Panel	Digital Computer	0.48	-0.54	0.29	0.44	-0.54	0.29	0.49	-0.44	0.19	0.04	0.01
12	VHF 2 Antenna	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
13	VHF 2 Transceiver	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
14	VHF 2 Control Panel	Digital Computer	0.48	-0.54	0.29	0.44	-0.54	0.29	0.49	-0.44	0.19	0.04	0.01
15	HF Antenna	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
16	HF Lightning Arrestor	Lights	0.24	-0.78	0.60	0.22	-0.76	0.58	0.49	-0.44	0.19	0.02	0.25
17	HF Antenna Coupler	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
18	HF Transceiver	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
19	HF Control Panel	Digital Computer	0.48	-0.54	0.29	0.44	-0.54	0.29	0.49	-0.44	0.19	0.04	0.01
20	Selcal Decoder	High-power/high-frequency components	0.96	-0.05	0.00	0.88	-0.10	0.01	0.73	-0.19	0.04	0.08	0.23
21	Selcal Control Panel	Digital Computer	0.48	-0.54	0.29	0.44	-0.54	0.29	0.49	-0.44	0.19	0.04	0.01
22	Passenger Address Amplifier 1	High-power/high-frequency components	1.92	0.91	0.83	1.76	0.78	0.61	1.47	0.54	0.29	0.16	0.46
23	Passenger Address Amplifier 2	High-power/high-frequency components	1.92	0.91	0.83	1.76	0.78	0.61	1.47	0.54	0.29	0.16	0.46
24	PA Speaker	High-power/high-frequency components	1.92	0.91	0.83	1.76	0.78	0.61	1.47	0.54	0.29	0.16	0.46
25	PA Speaker	High-power/high-frequency components	1.92	0.91	0.83	1.76	0.78	0.61	1.47	0.54	0.29	0.16	0.46
26	PA Speaker	High-power/high-frequency components	1.92	0.91	0.83	1.76	0.78	0.61	1.47	0.54	0.29	0.16	0.46
27	PA Speaker	High-power/high-frequency components	1.44	0.43	0.18	1.32	0.34	0.12	1.22	0.30	0.09	0.12	0.22
28	Cockpit Voice Recorder Control Panel	Digital Computer	0.48	-0.54	0.29	0.44	-0.54	0.29	0.49	-0.44	0.19	0.04	0.01
29	Cockpit Voice Recorder	Digital	0.24	-0.78	0.60	0.66	-0.32	0.10	0.73	-0.19	0.04	0.42	0.49
		SUM (Σ)	29.48		7.28	28.44		5.70	26.95		3.53	3.60	6.54
		MEAN = $\frac{\sum_{i=1}^{n} Xi}{n}$	1.02			0.98			0.93	MEAN Absolute Error =		0.12	0.23
	Standard Deviation (s) in hour =	$\sqrt{\Sigma}$ (x - mean)^2 / n-1	0.51			0.45			0.35				
		Variance (s^2) = Σ (x - mean)^2 / n-1			0.26			0.20			0.13		

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i|$$

Absolute Error (e_i) = $|f_i - y_i|$ where: f_i = the prediction value and y_i = the true value

The existing data has shown that MEAN is 1.02 hours whereas with LOG application the MEAN is 0.98 hours and with LINEAR application the MEAN is 0.93 hours. Therefore, the LOG formula seems better with 12% error (0.12/0.98) than the LINEAR formula with 25% error (0.23/0.93). Looking at the data in general the LOG formula is better than the LINEAR formula since the MEAN and Standard Deviation (s) values for the LOG formula are both closer to the EXISTING value than the values for the LINEAR formula. Also, the MEAN absolute error for the LOG formula is considerable smaller than for the LINEAR, also showing that this is a better fit.

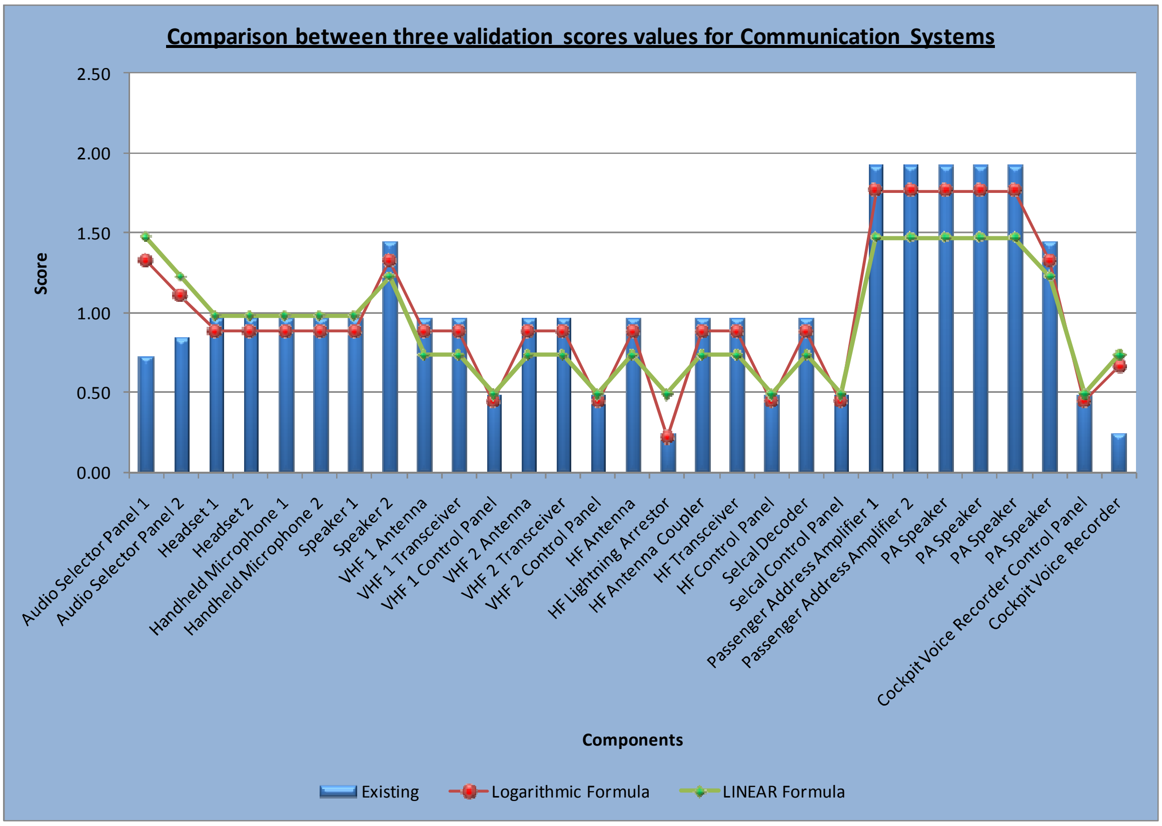


Figure 4—4 Comparison between all validation results for maintainability allocation

Validation of the findings is shown in the following chapter of this thesis. The detail of the testing and validation is also attached to this thesis and is depicted in the following appendices.

Appendix	*Title Name*
G	Testing and Validation of four selected trendlines
H.1	Testing results summary
I.1	Testing Case Study 1 Aircraft Fuel System
I.2	Testing Case Study 2 Aircraft Communications

As shown in Table 4-9, the errors are very small and therefore the selected formula works very well in allocating the correct score values to the new modules proposed. The percentage errors are calculated by Number of Acceptable errors divided by Number of Components. If the errors between predicted values and existing errors are between -0.5 and 0.5 (i.e. -0.5 ≤ Absolute Errors ≤ 0.5) they are considered to be acceptable. The acceptable values are equal to the Number of Acceptable errors.

This formula can now be used to add new modules as needed, as long as the maintenance task time is known. For this exercise the task time has been estimated using a maintainability prediction method; however, to be more accurate, the task time should come from the historical data or records.

Table 4-9 Summary of testing and validation results

Case Study	JASC	Title	No of Components	%		ABSOLUTE ERROR	
				LOG	LINEAR	LOG	LINEAR
1	28	Fuel	23	83.7%	91.3%	0.40	0.20
2	23	Communications	29	96.6%	96.6%	0.12	0.23

Finally, Table 4-10 shows both the existing and new list of modules and score values. These modules and values from the new list will be used in this research activity to predict the maintainability allocation prediction as well as to measure the effectiveness of maintainability prediction. The list is firstly arranged with the lowest score values up to the highest values. If there is more than one module with the same score values, then the list is arranged in alphabetical order.

Table 4-10 Comparison of existing and new lists of maintainability allocation

EXISTING MODULE AND SCORE		
No	Module	Score
1	Lights	1
2	Digital	1
3	Low-level analogue	1.5
4	High-level analogue	1.5
5	Digital Computers	2
6	Power Supplies	2
7	Electromechanical equipment	3
8	High-power/high-frequency components	4
9	Interconnections	4
10	Air conditioners	4
11	Liquid coolant systems	4
12	Mechanical Structures	6
13	Rotating mechanism/engines	10

NEW MODULE AND SCORE		
No	Module	Score
1	Lights	1
2	Digital	1
3	Low-level analogue	1.5
4	High-level analogue	1.5
5	Communications	2
6	Digital Computers	2
7	Power Supplies (Electrical/Electronic)	2
8	Actuator	3
9	Electromechanical equipment	3
10	Interconnections (Mechanical) - Pipe, Valve	3
11	Pump	3.5
12	Air conditioners	4
13	High-power/high-frequency components	4
14	Interconnections (Electrical)	4
15	Liquid coolant systems	4
16	Mechanical Structures	6
17	Mechanical Structures with Mechanism (i.e.: Landing Gear & Flight Control Surfaces)	8
18	Rotating mechanism/engines	10

4.6 Summary

The main contribution from this exercise is the LINEAR formula ($y = 1.4364x + 1.769$) can be used to calculate any other potential modules. In this research, author has proved that the mentioned formula has been used to calculate potential score value for new module. In the future more modules can be added and therefore offer accuracy in determining the allowable maximum task time for specific components.

5 Maintainability Prediction Methodology

The maintainability prediction methodology described in this section was performed in accordance with the steps described by Lipa [82], as shown below. Lipa described in detail the two types of maintainability prediction incorporated in MIL—HDBK-472 which are detail procedure and early procedure. Both of these procedures allow the designer to improve the design if the maintainability requirements are not met.

1. Define the prediction requirements;
   a. This includes defining the maintainability parameters to be evaluated.
   b. This involve defines the what, and when of maintenance.
2. Collect the prediction parameter data;
   a. All the necessaries data set such as failure rate are identified from reliable sources [155] and computed;
3. Select model;
   a. In this work procedure III was chosen as a maintainability prediction model based on decision making, as described in the previous chapter.
4. Compute;
   a. Maintainability parameters are computed in this step to find the potential task time for each individual component.

5.1 Objective

- to propose improvement to the maintainability prediction methodology to improve repeatability and accuracy.

5.2 Maintainability prediction – MIL-HDBK-472, Procedure III

In this section, each element of MIL-HDBK-472, procedure III will be described. Further, in checklist C of Human Factors all improved element will be described in detail.

5.2.1 **Checklist A – Design**

Checklist A contains all the questions that are related to product design. The questions are designed to help designers include or exclude the necessary elements such as BITE (Built in Test Equipment). The questions are developed to encourage designers to consider the element of maintainability through design. Collectively, the questions encourage designers to minimise additional tasks during maintenance activities. One of the examples is question 12: adjustments from checklist A as shown in Table 5-1, the designers have to design the components in such a way that no alignment necessary as possible to install the equipment back to operations as a solution to reduce the potential maintenance task time. One of the recommended solutions is that the components should be designed in one direction only, as shown in Figure 5—1.

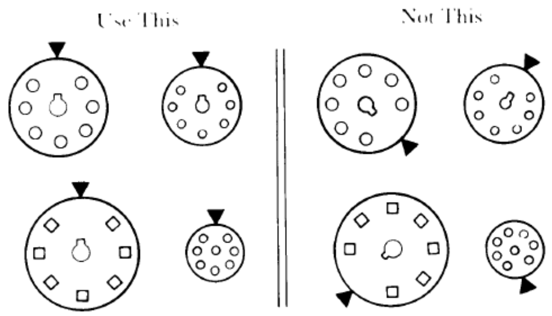


Figure 5—1 The recommended orientation for alignment [62]

Table 5-1 List of question in Checklist A, choice of answers, and score values [13]

Number	Scoring Physical Design Factors	Scores	Value
		CHECKLIST A - PHYSICAL DESIGN FACTORS	
1	Access (External)	Access adequate both for visual and manipulative tasks (electrical and mechanical)	4
		Access adequate for visual, but no manipulative	2
		Access adequate for manipulative, but not visual	2
		Access not adequate for visual or manipulative	0
2	Latches and Fasteners (External)	External latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release	4
		External latches and/or fasteners meet two of the above three criteria	2
		External latches and/or fasteners meet one or none of the above three criteria	0
3	Latches and Fasteners (Internal)	Internal latches and/or fasteners are captive, need no special tools, and require only a fraction of a turn for release	4
		Internal latches and/or fasteners meet two of the above three criteria	2
		Internal latches and/or fasteners meet one or none of the above three criteria	0
4	Access (Internal)	Access adequate both for visual and manipulative tasks (electrical and mechanical)	4
		Access adequate for visual, but no manipulative	2
		Access adequate for manipulaltive, but not visual	2
		Access not adequate for visual or manipulative	0
5	Packaging	Internal access to components and parts can be made with no mechanical disassembly	4
		Little disassembly required (less than 3 min)	2
		Considerable disassembly is required (more than 3 min)	0
6	Units - Parts (Failed)	Units or parts of plug-in nature	4
		Units or parts of plug-in nature and mechanically held	2
		Units of solder-in nature	2
		Units of solder-in nature and mechanically held	0
7	Visual Displays	Sufficient visual information on the equipment is given within one display area	4
		Two display areas must be consulted to obtain sufficient visual information	2
		More than two areas must be consulted to obtain sufficient visual information	0
8	Fault and Operation Indicatos (Built-In Test Equipment)	Fault or malfunction information is provided clearly and for rapid action	4
		Fault or malfunction information clearly presented but requires operator interpretation	2
		Fault or malfunction information requires no operator interpretation, but is not clearly presented	2
		Fault or malfunction information not clearly presented and requires operator interpretation	0
9	Test Points (Availability)	Task did not require use of test points	4
		Test points available for all needed tests	3
		Test points available for most needed tests	2
		Test points not available for most needed tests	0
10	Test Points (Identification)	All test points are identified with required readings given	4
		Some are suitably marked	2
		Points are not marked and test data are not given	0
11	Labelling	All parts labelled with full identifying information and all identifying information clearly visible	4
		All parts labelled with full identifying information , but some information hidden	2
		All information visible, but some parts not fully identified	2
		Some information hidden and some parts not fully identified	0
12	Adjustments	No adjustment or realignment is necessary to place equipment back in operation	4
		A few adjusments, but no major realignments are required	2
		Many adjustments or major realignment must be made	0
13	Testing (In Circuit)	Defective part or component can be determined without removal from the circuit	4
		Testing requires removal	0
14	Protective Devices	Equipment was automatically kept from operating after malfunction occurred to prevent further damage. (This refers to malfunction of such area as bias supplies, keep-alive voltage, etc.)	4
		Indicators warned that malfunction has occurred	2
		No provisons have been made	0
15	Safety (Personnel)	Task did not require work to be performed in close proximity to hazardous conditions (high voltage, radiation, moving parts and/or high temperature parts)	4
		Some delay encountered because of precautions taken	2
		Considerable time consumed because of hazardous conditions	0

The first four questions in checklist A focus on accessibility and types of latches and fasteners both externally and internally. One of the solutions to make the right decision and help identify the potential score value is by choosing the right latches or fasteners. At the same time, minimising the used of hand tools such as screwdrivers and wrenches is another solution to reduce potential maintenance task time. Task time reduction and design improvement includes the element of choosing the right latches or fasteners.

A new approach proposed in this report is to use a list of latches or fasteners. The latches and fasteners are categorised into several groups in accordance with latches and fasteners times. The less time required scores the highest value and the more time required scores the lowest value. Table 5-2 shows some recommendations for accessibilities and Table 5-3 shows the recommended types of fasteners.

Table 5-2 Recommended equipment accesses [62]

DESIRABILITY	FOR PHYSICAL ACCESS	FOR VISUAL INSPECTION ONLY	FOR TEST AND SERVICE EQUIPMENT
Most desirable	Pullout shelves or drawers	opening with no cover	Opening with no cover
Desirable	Hinged door (if dirt, moisture. or other foreign materials must be kept out)	Scratch-resistant plastic window (if dirt, moisture. or other foreign materials must be kept out)	Spring-loaded sliding cap (it dirt, moisture, or other foreign materials must be kept out)
Less desirable	Removable panel with captive, quick-opening fasteners (if there is not enough room for hinged door)	Break-resistant glass (if plastic will not stand up under physical wear or contact with solvents)	Removable panel with captive, quick-opening fasteners (if there is not enough room for hinged door)
Least desirable	Removable panel with smallest number of largest screws that will meet requirements (if needed for stress, pressure, or safety reasons)	Cover plate with smallest number of largest screws that will meet requirements (if needed for stress, pressure, or safety reasons)	Cover plate with smallest number of largest screws that will meet requirements (if needed for stress, pressure, or safety reasons)

Score Value	4	2	0
Time (in minutes)	0 - 3	4 - 7	8 and more
Fastener Types	Adjustable Pawl;	Dzus – Screw driver slot; Dzus – Wing Head; Captive – Knurled and Slotted Head	None
Latch types	Hook-hool Latch Trigger-Action Latch; Snapslide Latch; Hook Latch;	None	None
Chassis Mounted on Horizontal Shelf (Secured by screw fasteners through flange)	None	Captive Screw	Screw into tapped note with flat washer and lock washer; Screw through clearance holes with flat washer, lock washer, and nut; Screw through clearance holes with lock nut
Chassis Mounted on Horizontal Shelf (Secured by screw fasteners through chassis)	None	Captive Screw	Stud through chassis with flat washer, lock washer, and nut; Screw into stand-off with flat washer and lock washer
Chassis Mounted on Vertical Rack (Screw Fasteners into Frame)	None	Captive Screw	Thumb screw with lock washer and flat washers; Screw into tapped hole with flat washer and lock;
Chassis Mounted on Horizontal Shelf (Quick-Acting Fasteners)	Snap-slide latch; Dzus – type fastener; Spring or drawhook latch	None	None
Chassis Mounted on Vertical Rack (Quick-Acting Fasteners)	Push-button latch; Pawl latch 90° turn; Cam-action 90-180° turn of handle; Adjustable pawl latch	None	None

Table 5-3 The proposed scheme for questions 1, 2, 3, and 4 of checklist A (compiled by author) [62]

5.2.2 **Checklist B – Facilities**

The facilities questions in MIL-HDBK-472, procedure III, in checklist B focus on both human and equipment resources. Most of the questions asked are quite straightforward. All the questions and a description of each answer, and the score values are shown in Table 5-4.

To illustrate how straightforward the questions are, the following scenario is set as an example. Question 1 asks about external test equipment. Only four choices are available for the designer to choose from and decide on. Considering the landing gear hydraulic systems as an example, the mechanic and/or engineer might require only one equipment of hydraulic pressure test to measure the pressure on landing gear hydraulic systems in accordance with manufacturer's specification.

Therefore, the final answer will be two. As technology has increased and improved tremendously, there are some aircraft components that have been designed as remove and replacement (R&R); however, testing on new installations is still required. This is to ensure the installation satisfies an aircraft's operational requirements as well as checking that the installed components are functioning properly.

Table 5-4 List of Checklist B questions, choice of answers, and score values [13]

CHECKLIST B - FACILITIES			
1	External Test Equipment	Task accomplishment does not require the use of external test equipment	4
		One piece of test equipment is needed	2
		Several pieces (2 or 3) of test equipment are needed	1
		Four or more items are required	0
2	Connectors	Connectors to test equipment require no special tools fittings or adapters	4
		Connectors to test equipment require some special tools fittings or adapters (less than two)	2
		Connectors to test equipment require no special tools fittings or adapters (more than two)	0
3	Jigs or Fixtures	No supplementary materials are needed to perform task	4
		No more than one piece of supplementary materials is needed to perform task	2
		Two or more pieces of supplementary materials are needed	0
4	Visual Contact	The activities of each member are always visible to the other member	4
		On at least one occasion one member can see the second, but the reverse is not the case	2
		The activities of one member are hidden from the view of the other on more than one occasion	0
5	Assistant (Operations Personnel)	Task did not require consultation with operation personnel	4
		Some contact was required	2
		Considerable coordination required	0
6	Assistant (Technical Personnel)	Task required only one technician for completion	4
		Two technicians were required	2
		Over two were used	0
7	Assistant (Supervisors or Contractor Personnel)	Task did not require consultation with supervisor or contractor personnel	4
		Some help needed	2
		Considerable assistance required	0

The design team together with other teams such as Integrated Logistic Support (ILS) teams can decide and finally conclude the best score values in this checklist in accordance with the design of the components. This is discussed through several tools such Level of Repair Analysis (LORA) and Life Cycle Costing through forums such as the Maintenance Review Board (MRB). If the designer decides to assign the highest score value for one specific component and with the intention to have the minimum task time, therefore the designer has to identify suitable fasteners, latches, minimise number of remove and replace steps, as well as improve the design. MIL-HDBK-472, procedure III, allocates the highest score value (i.e. 4) to the most maintainable indication, and the lowest score value (i.e. 0) to the least maintainable indication.

5.2.3 **Checklist C – Human Factors**

Checklist C estimating the score value related to human capabilities. The capabilities are put into five categories, namely: Maximum effort (0 point), Above average effort (1 point), Average effort (2 points), Below Average effort (3 points), and Minimum effort (4 points). These points are very subjective and difficult to determine unless supported by quantitative-type of evaluation. In this research, the author decided to investigate any potential quantitative-type solution to determine the most suitable score value for each question in checklist C.

The designer should be able to consider the skills required and the personnel available to inspect and maintain equipment. The designer should also be able to reduce human error through design. Great understanding of human errors offers numerous benefits such as "*reduce the probability of damaged equipment or personnel injury"* [62]. This can be done through a better understanding of the limitations of humans. Human error includes [62]:

1. Failing to perform a task (omission);
2. Incorrectly performing a task;
3. Performing a task not required;
4. Performing a task out of sequence;
5. Failing to perform a task within the allocated time;
6. Responding inadequately to a contingency.

The human errors listed show a consistency with the objectives of this research development. This helps aircraft designers by drawing their intention to focus more efforts in their design to reduce or eliminate those errors. Such human error reduction or potential elimination can be performed through design activities. List item four, for instance, shows the necessity for design simplification and most importantly to include the element of procedure into maintainability prediction methodology.

Human factor decisions are very difficult to judge and measure. However, with help and advice from industry experts, the author proposed to use the human factor data in maintainability prediction methodology to help designers predict the potential task time in Checklist "C" of MIL-HDBK-472, procedure III. There are several references such as Woodson et al. [145] , Military Standard [156-158], and Garland et al. [159] that were used by author to identify the correct data and understand the characteristics of human data.

The generic approach proposed by the author in this research consists of three main elements: input, evaluation and output, as shown in Figure 5—2. The input element consists of all human factor elements and data [145]. The detail of human factor data used is described in the following section.

The second element, i.e. evaluation, is where the input is formulated before being channelled to the next element, i.e. output. If the results fall within minimum and maximum targets, the results are channelled to the output element where the final decision is concluded from the score values of 4 (Minimum effort), 3 (Below average effort), 2 (Average effort), 1 (Above average effort), or 0 (Maximum effort).

Figure 5—2 Process of evaluations of MIL-HDBK-472, Procedure III, Checklist C

5.2.4 Arm, Leg and Back Strength

In this scenario the author decided to use human strength in the form of a percentage (%). Table 5-5 shows the percentage distribution for the purpose of score value evaluation. If the strength required to perform and complete a specific task is 30%, then the score value will be 3 because 30% is within the range of 25% to 50%. The range is equally distributed in order to cater for the five available score values.

Table 5-5 Percentage distribution for Arm, Leg and Back Strength [144; 145]

Score	**4**	**3**	**2**	**1**	**0**
Strength (%)	5	25	50	75	100

5.2.5 Endurance and Energy

In this scenario the author decided to evaluate the score values by using the maximum load lift limits. Other types of data can be used for human energy in relation to the types and time works to perform. For this research, the maximum load lift limits were chosen because the author assumed that the maintenance task performed related to removal and reassembly. The data shown in **Table 5-6** were used.

Table 5-6 Average maximum load lift for male[158]

Distance (up to) in inches	36	60	Average
Males (in lbs)	87	56	71.5

The purpose of this paragraph is to illustrate further how the maximum load lifts are formulated. Table 5-6 shows the values for the average maximum load lift for both male and female. The author had to formulate the available data into five categories and be able to contribute to the available score values (i.e. 0, 1, 2, 3 and 4) with each score value representing the level of effort required by a human to perform and complete the tasks. An average of a data set is a measure of the "middle" value of the data set. Therefore the "middle" value between zero and ten is equal to five. By using this theory, therefore, five values are equal to an average maximum load lift.

The score values are categorised into five categories: 1) Minimum (4 points); 2) Below Average (3 points); 3) Average (2 points), 4) Above Average (1 point), and 5) Maximum (0 points). In order to fit with the checklist C score values, the data are distributed into five categories as shown in Table 5-7.

Table 5-7 An average lifting weight for male

Score Value	4	3	2	1	0
Average Weight (lbs)	0-17	18 - 35	36 - 51	52 – 86	87 or more

Figure 5—3 illustrates that humans require highest strength percentage for minimum time and less percentage of strength capable to have more time required to perform and complete specific tasks.

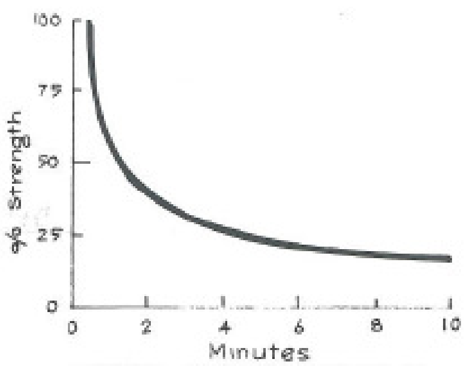


Figure 5—3 The typical endurance time in relation to force requirement [145]

5.2.6 **Planfulness and Resourcefulness**

In this category of questions, the author proposed and decided to use the element of the number of resources required to perform and complete the necessary tasks. If the number of resources is the minimum (i.e. only a screwdriver) then this indicates that the performer requires minimum effort to complete the task and therefore the score value will be 4. However, if the necessary number of resources required is more than five for instance, then the score value could be less. This means the effort required to perform and complete the specific task could be in the average or above average range, depending on how the allocation of the number of resources required is assigned.

In this research, the author decided to assign a minimum of two resources required for minimum efforts and then increased by two for each score (i.e. 2, 4, 6, 8, and 10). This means that if the works requires more than 10 resources of equipment and/or tools to perform and complete the tasks, then the score will be zero which means maximum effort is required. This is because the mechanic/engineer has to be familiar and organised to ensure the proper equipments and/or tools are used effectively.

5.2.7 **Others**

For the rest of the questions, as listed below, the author's decision was based on understand the meaning and interpretation of each question. This is because each question focuses on personal skills to organise and give attention to the work to be performed.

1. Eye-hand Coordination, Manual Dexterity and Neatness (Question 3)
2. Visual Acuity (Question 4)
3. Logical Analysis (Question 5)
4. Memory - Things and Ideas (Question 6)
5. Alertness, Cautiousness and Accuracy (Question 8)
6. Concentration, Persistence and Patience (Question 9)
7. Initiative and Incisiveness (Question 10)

If the mechanic and/or aircraft engineer has more experience, this person may more organised compared to the person with less experience in performing specific tasks. However, it is very difficult to judge people's experience at the design and development stage. Therefore, the author decided to use the element of number of procedures to generate a suitable outcome.

The fewer procedures needed for specific equipment means the effort in the above categories required will be minimised but if there are more procedures to follow, then there will be greater effort required to perform and complete the task. The rationale is that the person performing the task has to understand the procedure correctly and be organised. Under these circumstances the proposed approach strongly advises the designer to simplify the product design as much as possible and offer minimum procedure to complete the task. Table 5-8 show the distribution of number of steps for each individual component. If one specific component required 4 steps to remove and replace the component therefore the score value is equal to 3. The final table is shown in Table 5-9.

Table 5-8 Distribution for question number 3, 4, 5, 6, 8, 9, and 10

Score Value	Description
4	Number of steps = 3 or less
3	Number of steps = 4 to 6
2	Number of steps = 7 to 9
1	Number of steps = 10 to 12
0	Number of steps more than 13

Table 5-9 The final list of Checklist C - Human Factor

Questions	1	2	3	4	5	6	7	8	9	10	SCORE	DESCRIPTION
Distribution	5	17.0	3	3	3	3	3	3	3	3	4	Minimum efforts
	25	35.0	6	6	6	6	6	6	6	6	3	Below average efforts
	50	51.0	9	9	9	9	9	9	9	9	2	Average efforts
	75	86.0	12	12	12	12	12	12	12	12	1	Above average efforts
	100	150.0	15	15	15	15	15	15	15	15	0	Maximum efforts
	% of strength	Weight (lbs)	No of Steps	No of Steps	No of Steps	No of Steps	Number of Resources (Qty)	No of Steps	No of Steps	No of Steps		

Table 5-11 illustrate how the final score value for each individual for checklist C. For an example, assume hydraulic components weigh 8 kilo average, number of steps to remove and replace are 8 steps by using standard tools (i.e. wrenches and flat screw driver). Estimation to remove and replace each individual component is five minutes in average. The explanation is shown in Table 5-10.

Table 5-10 Checklist C score value explanation

Question	Score description
1	Hydraulic component weight 8 kilo falls between 5 and 25, therefore the score is equal to 3
2	Average time to remove and replace is equal to five minutes, therefore the strength required is approximately 25% and the score value is equal to 4
3	There are 8 steps to remove and replace the components, therefore the score value is equal to 3
4	
5	
6	
7	The process is perform by using standard tools, therefore less than 3 recourses the score equal to 4
8	There are 8 steps to remove and replace the components, therefore the score value is equal to 3
9	
10	

Table 5-11 Final result for Checklist C – Human Factor, maintainability prediction

Question	Checklist C	Input	Output
1	Arm, Leg and Back Strength	8	4
2	Endurance and Energy	25	4
3	Eye-hand Coordination, Manual Dexterity and Neatness	8	3
4	Visual Acuity	8	3
5	Logical Analysis	8	3
6	Memory - Things and Ideas	8	3
7	Planfulness and Resourcefulness	4	4
8	Alertness, Cautiousness and Accuracy	8	3
9	Concentration, Persistence and Patience	8	3
10	Initiative and Incisiveness	8	3

5.3 Testing and Case Study

The new maintainability prediction methodology was tested by using a case study. In the initial stage of maintainability prediction testing, the author prepares a generic list of landing gear components, as shown in Table 5-12. The purpose of performing this initial stage of maintainability prediction is to ensure the author has a better understanding of MIL-HDBK-472, procedures III, and to identify the strengths and drawbacks of this approach for the purpose of further improvement.

As a result, the author found difficulty in identifying suitable score values for each question in checklist C which related to human factors. This is one of the opportunities identified by the author to propose a new approach. A methodology and improved approach to checklist C has been described previously in Chapter 3, section 3.3.

Table 5-12 The generic list of landing gear components

No	Check List A: DESIGN	Struts	Tires	Brakes	Actuators	Wheels	Steering	Hydraulic	Anti Skid	Structure	Attachments
	References: CAAIP	Part 6-3, pg 2	Part 6-3, pg 2	Part 6-3, pg 2	Part 5-10, pg 10	Part 6-3, pg 2	Part 5-8, pg 2	Part 6-3, pg 5	Part 5-8, pg 15	Part 6-3, pg 2	Part 6-3. pg 2
1	Access (External)	4	4	4	4	4	4	4	4	4	4
2	External latches and/or fasteners	4	4	4	4	4	4	4	4	4	2
3	Internal latches and/or fasteners	4	4	4	4	4	4	4	4	4	4
4	Access (Internal)	4	4	4	4	4	4	4	4	4	4
5	Packaging	0	0	0	0	0	0	0	0	0	0
6	Units - Part (Failed)	2	2	2	2	2	2	2	2	2	4
7	Visual Display	4	4	4	4	4	4	4	4	4	4
8	Fault and Operation Indicators (BITE)	2	2	2	2	2	2	2	2	2	4
9	Test Points (Availability)	4	4	2	2	4	2	2	2	4	4
10	Test Points (Identifications)	2	4	2	2	4	2	4	2	2	2
11	Labelling	4	4	4	4	4	4	4	4	4	4
12	Adjustments	0	2	2	2	4	0	2	2	0	2
13	Testing (In Circuit)	4	0	0	0	0	4	0	0	4	4
14	Protective Devices	4	4	4	4	4	4	4	4	4	0
15	Safety (Personnel)	2	2	2	2	2	2	0	2	2	4
		44	**44**	**40**	**40**	**46**	**42**	**40**	**40**	**44**	**46**

No	Check List B: FACILTIES	Struts	Tires	Brakes	Actuators	Wheels	Steering	Hydraulic	Anti Skid	Structure	Attachments
		Part 6-3, pg 2	Part 6-3, pg 2	Part 6-3, pg 2	Part 5-10, pg 10	Part 6-3, pg 2	Part 5-8, pg 2	Part 6-3, pg 5	Part 5-8, pg 15	Part 6-3, pg 2	Part 6-3. pg 2
1	External Test Equipment	2	4	2	1	4	2	1	1	2	4
2	Connectors	4	0	0	0	0	4	4	4	4	4
3	Jigs or Fixtures	4	0	0	0	0	4	4	4	4	4
4	Visual Contact	4	4	4	4	4	4	4	4	4	4
5	Assistance (Operational Personnel)	2	2	2	2	2	2	2	2	2	2
6	Assistance (Technical Personnel)	4	2	2	4	2	4	4	2	4	4
7	Assistance (Supervisor or Contractor Personnel)	4	4	4	4	4	4	4	4	4	4
		24	**16**	**14**	**15**	**16**	**24**	**23**	**21**	**24**	**26**

No	Check List C: Maintenance Skills (Human Factors)	Struts	Tires	Brakes	Actuators	Wheels	Steering	Hydraulic	Anti Skid	Structure	Attachments
		Part 6-3, pg 2	Part 6-3, pg 2	Part 6-3, pg 2	Part 5-10, pg 10	Part 6-3, pg 2	Part 5-8, pg 2	Part 6-3, pg 5	Part 5-8, pg 15	Part 6-3, pg 2	Part 6-3. pg 2
1	Arm, Leg, and Back Strength	4	2	2	4	2	4	4	2	4	2
2	Endurance and Energy	2	2	2	2	2	2	2	2	2	2
3	Eye-hand Coordination,Manual Dexterity and Neatness	2	2	2	0	2	2	0	2	2	2
4	Visual Acuity	2	2	2	2	2	2	2	2	2	2
5	Logical Analysis	0	2	2	1	2	2	1	2	0	1
6	Memory - Things and Ideas	2	2	4	2	4	2	2	4	2	1
7	Planfulness and Resourcefulness	2	2	2	2	2	2	2	2	2	0
8	Alertness, Cautiousness and Accuracy	0	2	0	0	4	0	0	4	0	2
9	Concentration, Persistence and Patience	0	2	2	0	2	0	0	2	0	2
10	Initiative and Incisiveness	0	2	2	2	2	2	2	2	0	2
		14	**20**	**20**	**15**	**24**	**18**	**15**	**24**	**14**	**16**
	Mct (Minutes)	35.89	54.18	78.60	83.08	43.64	36.44	47.33	43.44	35.89	26.41
	Mct (Hour)	0.60	0.90	1.31	1.38	0.73	0.61	0.79	0.72	0.60	0.44

The following process was tested by using a case study. The selected case study was aircraft fuel systems from a twin–engine long haul aircraft. With regard to the references for a case study, the author used the acceptable method for aircraft maintenance known as CAAIP [107].

5.3.1 **Case Study – Aircraft Fuel Systems**

The main purpose of this exercise is to test the developed quantitative methodology (i.e. MIL-HDBK-472, procedure III in checklist C) by author. The results from this case study were performed by using the developed approach and then compare with predicted maintainability by Bineid [141], which is the fuel system of a twin-engine long haul aircraft. A case study presented in this report is for right and left fuel systems. In Table 5-13 show the predicted maintenance time for each individual component for aircraft fuel system.

Table 5-13 List of predicted maintenance corrective times [141]

No	LRU	Maintenance Corrective time (hour)
1	Hand Pump	0.47
2	Reservoir Fill Selection Valve (RFSV)	0.40
3	Pressure Valve (PV)	0.40
4	Reservoir	1.01
5	Non Return Valve (NRV)	0.47
6	Engine Driven Pump (EDP)	0.76
7	Non Return Valve (NRV)	0.47
8	Aircraft Motor Pump (ACMP)	1.71
9	Non Return Valve (NRV)	0.47
10	Pipe	0.92
11	Pump Overheat Light (POL 1)	0.69
12	Pump Overheat Light (POL 2)	0.69
13	Pump Low Light (PLL 1)	0.36
14	Pump Low Light (PLL 2)	0.36
15	Heat Exchanger (HEX)	1.16
16	Hydraulic Low Light (HLL 1)	0.30
17	Hydraulic Low Light (HLL 2)	0.30
18	Hydraulic Low Light (HLL 3)	0.30
19	Hydraulic Quantity Indicator (HQ 1)	0.33
20	Hose	0.13
21	Depressurisation Valve (DPV)	0.15
22	Non Return Valve (NRV)	0.47
23	Moisture Vent Trap (MVT)	0.73

The improvement of the maintainability prediction presented in this section is focused on focused on Checklist C - Human Factor of MIL-HDBK-472, procedure III as shown in Table 5-14.

Table 5-14 List of questions from checklist C

	Check List C: Maintenance Skills (Human Factors)
1	Arm, Leg, and Back Strength
2	Endurance and Energy
3	Eye-hand Coordination, Manual Dexterity and Neatness
4	Visual Acuity
5	Logical Analysis
6	Memory - Things and Ideas
7	Planfulness and Resourcefulness
8	Alertness, Cautiousness and Accuracy
9	Concentration, Persistence and Patience
10	Initiative and Incisiveness

All description and quantitative methodology for checklist C has been described previously in section 3.3.2. In this testing exercise, some of the information is not accessible; therefore the author used the generic assumption. The assumptions based on authors' analysis which have been presented in Table 5-6 & Table 5-8. The assumption includes the average strength required is equal to 71.5% (see Table 5-6) and the average weight of each component is equal to 18 lbs (see Table 5-7). These assumptions allow author to assign suitable score value for question 1 and question 2.

For question 3, 4, 5, 6, 8, 9, and 10, the score value is assign in accordance with number of steps required to remove and replace the components. The information of number of steps are identified from acceptable methods, techniques, and practices or known as CAP 562: Civil Aircraft Airworthiness Information and Procedures (CAAIP) [107]. CAAIP is an acceptable methods, techniques and practices as well as minimum guidelines to perform any maintenance tasks.

Meanwhile for question 7: Planfulness and Resourcefulness, the assumption made based on CAAIP. On average after reviewing the CAAIP document, the average resource required to perform the removal and replace tasks is five resources such as standard wrenches, standard screw driver, locking wire, and disposable materials. Some components required less than three resources such as valve, pipe, and light bulb.

5.3.2 Testing results and discussion

In Table 5-15 show the results summary for the aircraft fuel systems testing and illustrated in Figure 5—4. Clearly, the improved checklist C of Human Factor in MIL-HDBK-472, procedure III is capable to make some contribution in maintainability predictions. The most important lesson learned from this piece of work is not only about the potential of improvement using either a developed approach or any other approach. The author’s viewpoint is how can researchers include the element of human data into one specific methodology and as a result contribute several benefits for aircraft designers, as well as human error reduction.

Most importantly, the results show that designer has capabilities to improve maintenance task time by understanding the human capabilities. Table 5-16 show the maintainability prediction before the implementation of improvements and Table 5-17 shows the final results after improvements by using the developed approach.

Table 5-15 Case study - Results summary

No	LRU	Maintenance Corrective time (hour)		Error
		Bineid results [141]	Author results	
1	Hand Pump	0.47	0.44	0.03
2	Reservoir Fill Selection Valve (RFSV)	0.40	0.40	0.00
3	Pressure Valve (PV)	0.40	0.40	0.00
4	Reservoir	1.01	0.92	0.09
5	Non Return Valve (NRV)	0.47	0.48	-0.01
6	Engine Driven Pump (EDP)	0.76	0.72	0.04
7	Non Return Valve (NRV)	0.47	0.48	-0.01
8	Aircraft Motor Pump (ACMP)	1.71	1.58	0.13
9	Non Return Valve (NRV)	0.47	0.48	-0.01
10	Pipe	0.92	0.83	0.09
11	Pump Overheat Light (POL 1)	0.69	0.64	0.05
12	Pump Overheat Light (POL 2)	0.69	0.48	0.21
13	Pump Low Light (PLL 1)	0.36	0.34	0.02
14	Pump Low Light (PLL 2)	0.36	0.48	-0.12
15	Heat Exchanger (HEX)	1.16	1.04	0.12
16	Hydraulic Low Light (HLL 1)	0.30	0.30	0.00
17	Hydraulic Low Light (HLL 2)	0.30	0.30	0.00
18	Hydraulic Low Light (HLL 3)	0.30	0.30	0.00
19	Hydraulic Quantity Indicator (HQ 1)	0.33	0.34	-0.01
20	Hose	0.13	0.13	0.00
21	Depressurisation Valve (DPV)	0.15	0.15	0.00
22	Non Return Valve (NRV)	0.47	0.48	-0.01
23	Moisture Vent Trap (MVT)	0.73	0.59	0.14

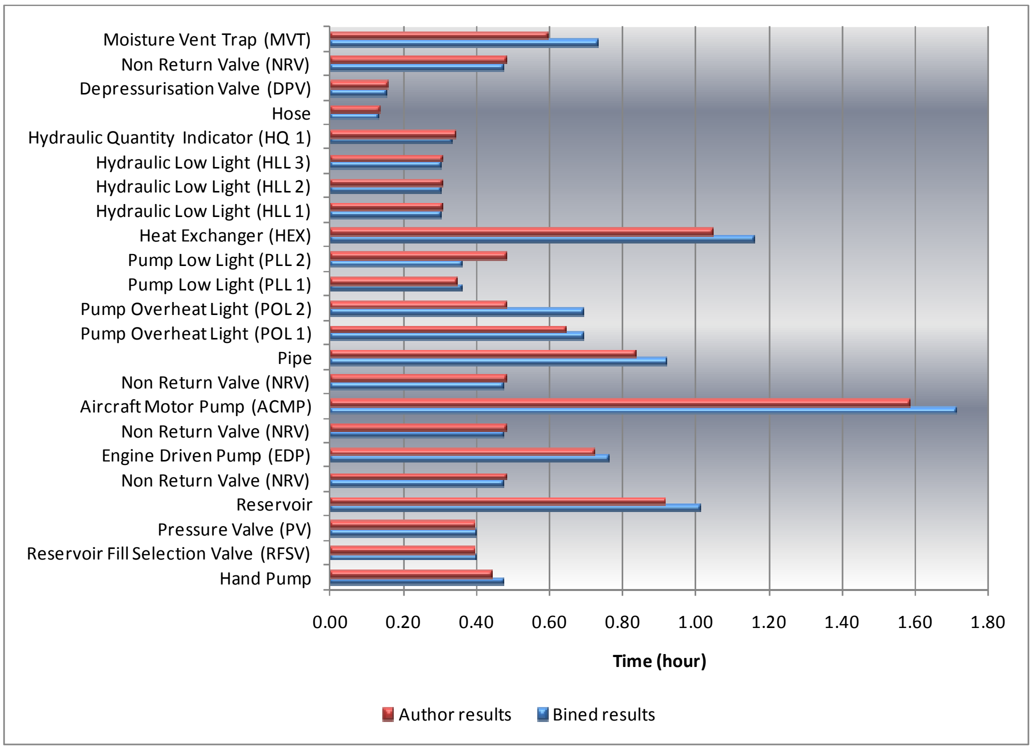


Figure 5—4 Case study - Testing results

5.4 Summary

The main outcome and success of this chapter is the author is able to identify, developed, and improved maintainability prediction methodology specifically in checklist C Human Factor. Traditionally, score value in checklist C is difficult to allocate. This is because the available range of selection is too subjective (i.e.: Below Average, Average, Above Average). By using human data, this research is able to allocate and determine suitable score value for each questions.

Table 5-16 The maintainability prediction before improvement [141]

	Check List C - Scoring Design Dictates - Maintenance Skills		Hand Pump	RFSV	PV	Reservoir	NRV	EDP	ACMP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurisation Valve	Moisture vent trap
1	Arm, Leg, and Back Strength	0-1-2-3-4	3	3	2	2	4	2	3	2	2	2	2	2	4	4	4	3
2	Endurance and Energy		2	3	4	2	4	2	2	2	3	4	2	4	4	4	4	3
3	Eye-hand Coordination,Manual Dexterity and Neatness		3	4	4	2	4	2	2	2	3	3	2	4	4	4	4	3
4	Visual Acuity		3	4	4	2	3	2	2	2	2	2	3	4	4	4	4	3
5	Logical Analysis		3	4	4	2	3	4	2	2	2	2	2	3	4	3	3	3
6	Memory - Things and Ideas		3	4	4	2	3	3	2	2	2	2	3	4	4	4	2	3
7	Planfulness and Resourcefulness		2	4	4	2	3	4	2	2	2	2	2	4	3	4	2	3
8	Alertness, Cautiousness, and Accuracy		4	3	3	2	3	3	2	2	3	4	2	4	3	4	4	3
9	Concentration, Persistence and Petience		3	4	3	2	3	3	2	2	3	4	2	3	3	4	4	3
10	Initiative and Incisiveness		3	3	4	2	3	3	2	2	3	4	2	4	3	3	4	3
	TOTAL		**29**	**36**	**36**	**20**	**33**	**28**	**21**	**20**	**25**	**29**	**22**	**36**	**36**	**38**	**35**	**30**
	Predicted Downtime																	
	A	0.02512 A	1.2560	1.1053	1.1053	1.0550	1.0048	1.1555	0.8792	1.0048	1.1053	1.2811	0.8541	1.2811	1.1806	1.4570	1.4067	1.1053
	B	0.03055 B	0.5194	0.6721	0.6721	0.4888	0.7332	0.4277	0.4277	0.5805	0.5499	0.6110	0.6110	0.6110	0.6721	0.7943	0.7943	0.5499
	C	0.01093 C	0.3170	0.3935	0.3935	0.2186	0.3607	0.3060	0.2295	0.2186	0.2733	0.3170	0.2405	0.3935	0.3935	0.4153	0.3826	0.3279
	3.54651-0.02512A-0.03055B-0.01093C		1.4542	1.3757	1.3757	1.7841	1.4478	1.6573	2.0101	1.7427	1.6181	1.3374	1.8410	1.2609	1.3003	0.8799	0.9629	1.5634
	MTTR	**MINUTES**	**28.46**	**23.75**	**23.75**	**60.82**	**28.04**	**45.42**	**102.35**	**55.29**	**41.50**	**21.75**	**69.34**	**18.24**	**19.97**	**7.58**	**9.18**	**36.60**
	MTTR	**HOUR**	**0.47**	**0.40**	**0.40**	**1.01**	**0.47**	**0.76**	**1.71**	**0.92**	**0.69**	**0.36**	**1.16**	**0.30**	**0.33**	**0.13**	**0.15**	**0.61**

Table 5-17 The maintainability prediction after improvement by using a developed approach

	Check List C - Scoring Design Dictates - Maintenance Skills	SCORE	Hand Pump	RFSV	PV	Reservoir	NRV	EDP	ACMP	Pipe	POL	PLL	Heat Exchanger	HLL	HQI	Hose	Depressurisation Valve	Moisture vent trap
1	Arm, Leg, and Back Strength	0-1-2-3-4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
2	Endurance and Energy		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3	Eye-hand Coordination,Manual Dexterity and Neatness		3	4	4	2	4	2	2	2	3	3	2	4	4	4	4	3
4	Visual Acuity		3	4	4	2	3	2	2	2	2	2	3	4	4	4	4	3
5	Logical Analysis		3	4	4	2	3	4	2	2	2	2	2	3	4	3	3	3
6	Memory - Things and Ideas		3	4	4	2	3	3	2	2	2	2	3	4	4	4	2	3
7	Planfulness and Resourcefulness		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
8	Alertness, Cautiousness, and Accuracy		4	3	3	2	3	3	2	2	3	4	2	4	3	4	4	3
9	Concentration, Persistence and Petience		3	4	3	2	3	3	2	2	3	4	2	3	3	4	4	3
10	Initiative and Incisiveness		3	3	4	2	3	3	2	2	3	4	2	4	3	3	4	3
	TOTAL		**32**	**36**	**36**	**24**	**32**	**30**	**24**	**24**	**28**	**31**	**26**	**36**	**35**	**36**	**35**	**31**
	Predicted Downtime																	
	A	0.02512 A	1.2560	1.1053	1.1053	1.0550	1.0048	1.1555	0.8792	1.0048	1.1053	1.2811	0.8541	1.2811	1.1806	1.4570	1.4067	1.1053
	B	0.03055 B	0.5194	0.6721	0.6721	0.4888	0.7332	0.4277	0.4277	0.5805	0.5499	0.6110	0.6110	0.6110	0.6721	0.7943	0.7943	0.5499
	C	0.01093 C	0.3498	0.3935	0.3935	0.2623	0.3498	0.3279	0.2623	0.2623	0.3060	0.3388	0.2842	0.3935	0.3826	0.3935	0.3826	0.3388
	3.54651-0.02512A-0.03055B-0.01093C		1.4214	1.3757	1.3757	1.7404	1.4588	1.6354	1.9773	1.6989	1.5853	1.3156	1.7973	1.2609	1.3112	0.9018	0.9629	1.5525
	MTTR	**MINUTES**	**26.39**	**23.75**	**23.75**	**55.00**	**28.76**	**43.19**	**94.91**	**50.00**	**38.48**	**20.68**	**62.70**	**18.24**	**20.47**	**7.98**	**9.18**	**35.69**
	MTTR	**HOUR**	**0.44**	**0.40**	**0.40**	**0.92**	**0.48**	**0.72**	**1.58**	**0.83**	**0.64**	**0.34**	**1.04**	**0.30**	**0.34**	**0.13**	**0.15**	**0.59**

6 Integrated Methodology

This research utilises the aircraft maintenance related feedback information in maintainability prediction methodology. Figure 6—1 shows overall methodology of the maintainability prediction process for aircraft mechanical components proposed in this research and described in detail in Chapter 3.

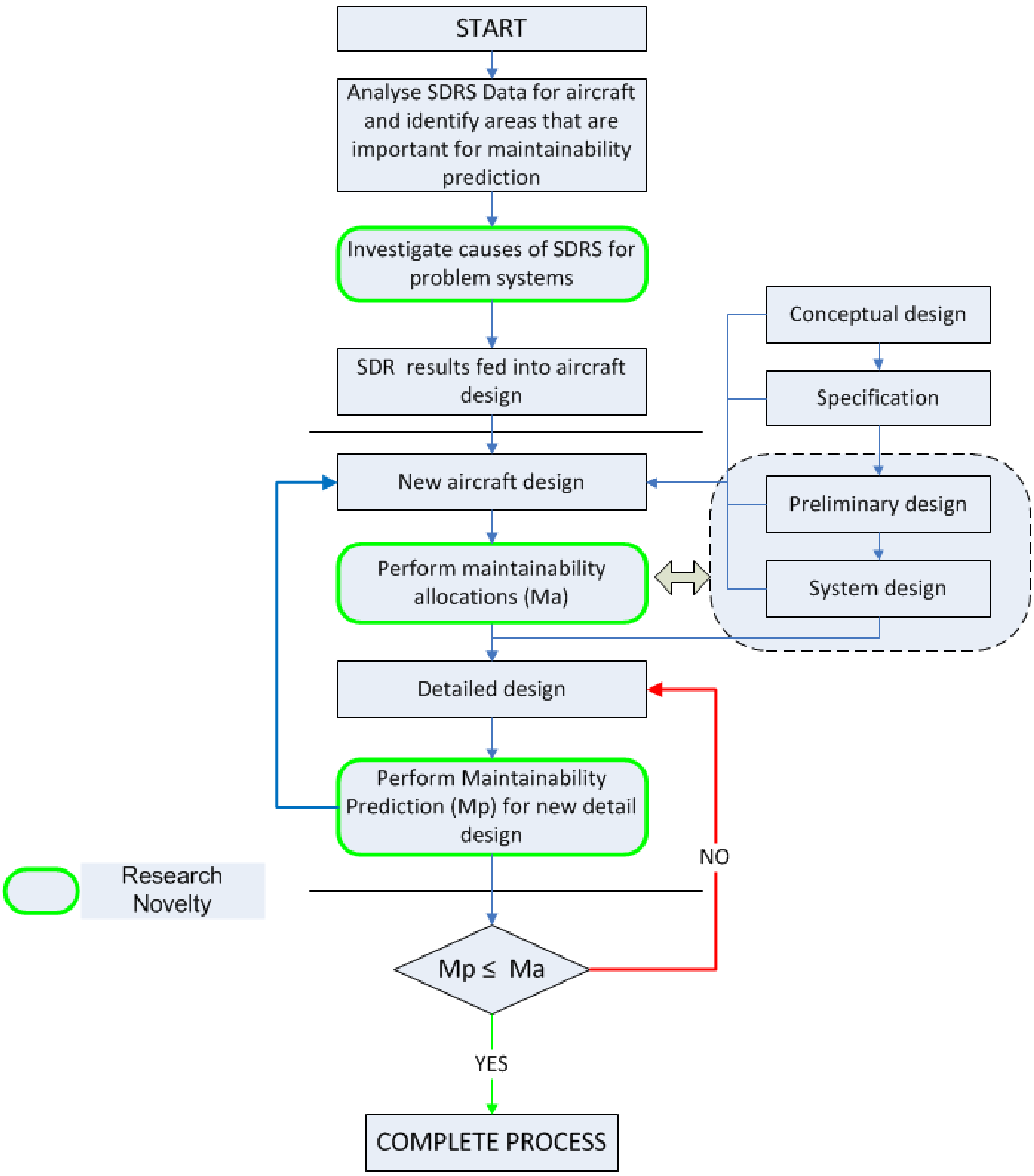


Figure 6—1 The maintainability prediction for the aircraft components methodology

6.1 Maintainability prediction process

The maintainability prediction is performed to achieve a more accurate prediction rather than predicting the lowest task time. The processes consist of two, namely Service Difficulties Report, Maintenance allocation, and Maintenance prediction.

6.1.1 Service Difficulties Report

The first process was to identify and analyse the feedback information related to maintenance difficulties and determine the maintainability effectiveness. The process of analysing the feedback information is in accordance with Figure 3—3.

6.1.2 Maintenance allocation

The second process was determining the effectiveness of maintainability prediction is by using estimating the maintenance allocation time for each individual component by using the following Table 6-1 and steps:

Table 6-1 Maintainability allocation analyses report [14]

No	Components	List of Modules	Allocation (Kj)			Σ Kj	λ or SR	$\lambda j\,Kj$	Allocated R*pj* (hour)	λR*pj*
			Module	Isolation	Accessiblity					
	2			3		4	5	6	7	8

TOTAL (Σ)	λ or SR	$\lambda j\,Kj$		λR*pj*

MTTR	1.00	Estimation 1
K = Σλ*j* K*j* / ΣFR		
Rpj = (MTTR/K)*K*j*		
Check: MTTRsystem = ΣλRpj/λ		

Step 1 Identify or Calculate the Mean Time to Repair (MTTR) requirement. The MTTR can be predicted or calculated by using Equation 4-6;

Step 2 Enter the basic information regarding the system, sub-system, components;

Step 3 Enter the weight factor (Kj1, Kj2, and Kj3);

Step 4 Calculate the total score value for each component;

Step 5 Enter the value of failure rate (λ) and/or Service difficulties rate (SR). The SR values are calculated by using Equation 3-1; If the SR (Service Difficulties) is used, change the failure rate (λ) to SR values.

Step 6 Calculate the contribution of maintainability allocation time for each component by using Equation 4-1;

Step7 Calculate the Allocated Rpj for each individual component by using Equation 4-2;

Step 8 To ensure the allocation for each component meet the MTTR requirement, compute the to system by using Equation 6-1; If the computed of MTTR is equal to the MTTR requirement, the result will show as PASSED, and if not then the result will show as FAILED

$$MTTR = \frac{\Sigma\lambda jRpj}{\lambda}$$ **Equation 6-1**

6.1.3 Maintenance prediction

Step 1 Estimate the Corrective Maintenance Time (M_{ct}) of individual maintenance tasks using the following Table 6-2[13];

Table 6-2 Maintainability prediction methodology [13]

Check List	Questions															TOTAL
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
A																
B																
C																
										Corrective Maintenance Time (Mct)						

Step 2 Calculate the total score values for each component and calculate the predicted maintenance corrective time by using Equation 6-2.

M_{ct} = antilog (3.54651 – 0.02512A – 0.03055B – 0.01093C) **Equation 6-2**

M_{ct} = Maintenance Corrective Time
A = Checklist A: Physical Design Factor;
B = Checklist B: Facilities
C = Checklist C: Maintenance Skills

Step 3 Compare the predicted Maintenance Corrective Time (M_{ct}) and Maintainability Allocation (Rpj). As the M_{ct} is equal to or less than Maintenance Allocation time (Rpj), then the decision is “GOOD”. If the decision is “NOT GOOD”, repeat step no 1 in maintenance prediction and/or simplify the design;

6.2 Research methodology - summary

This approach is able to assist aircraft designers to improve their design by providing the maximum target maintenance task time for each individual aircraft components and/or systems. The maintainability prediction of each individual aircraft component and/or system is performed after the target maintenance task time has been assigned. If the predicted values are equal to or below the targeted time, then the maintainability is acceptable. However, if the individual predicted task time is above the allocated task time, then it is not acceptable and a redesign is one of the solutions. Figure 6—2 show the process flow for both maintainability allocation and prediction methodologies developed by the author.

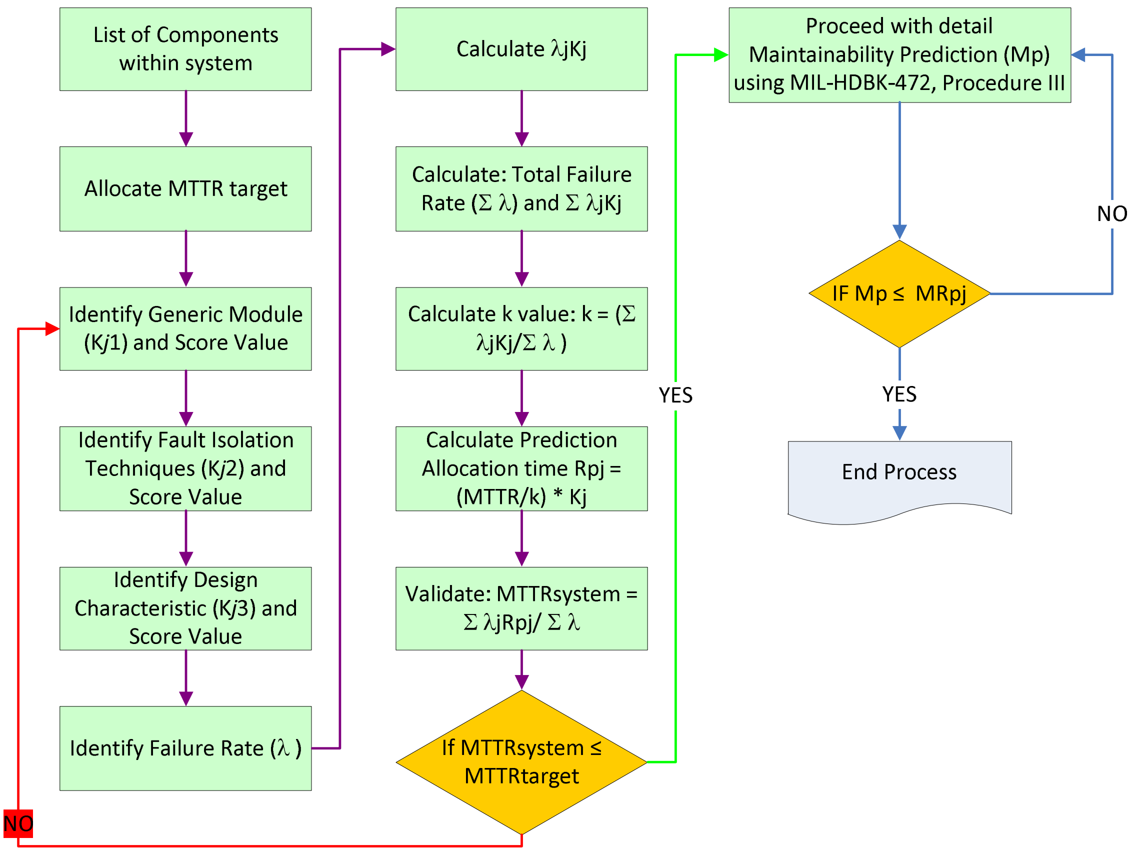


Figure 6—2 Process flow of maintainability allocation and prediction methodology

This research has been carried out based on the outline strategies previously described in section 1.8. The process begins with analysing the SDR as per described in chapter 3. Furthermore, the maintainability allocation methodology has been used to ensure this research achieved the targeted aim and research objectives. The descriptions of the selected techniques are given in chapter 4. The maintainability prediction methodology has been reviewed, and is described in chapter 5. After the existing maintainability prediction methodologies have been carried out, the author has been able to conclude the following:

1. The existing prediction methodologies rely on failure rate (λ) as a main input to estimate the effectiveness of maintainability predictions;
2. The failure rate (λ) can be multiplied by individual maintenance task times, in order to estimate maintainability effectiveness;
3. Existing prediction methodologies are able to estimate maintainability effectiveness for each individual system or sub system; however, there is no indication whether the estimated values are within limits or off limits;
4. The table can be redesigned with the intention of providing allocation time for maintainability. The methodology of providing allocation time is described in the next section of this thesis.

Others element that should be considered is the element of mechanical components (i.e.: Mass, Number of Components assembled). In order to meet the maintenance allocation target as well as to improve maintenance prediction time number of components assembled for example should be reviewed. This could also include the consideration of eliminate the unnecessary component. The element of mass could also be improved. Through these considerations, the overall aircraft systems design process can be implemented.

7 Validation

The aim of this chapter is **to apply the integrated maintainability prediction methodology** and **to compare the predicted values to the real world values** (i.e.: Maintenance tasks time).

One of the most challenges in this research has been to obtain real world maintenance task times from industry. Due to these restrictions, the author proposed using the element of target-value. Target-value is the termed used by the author to represent the maximum allowable task time for individual aircraft mechanical components or systems. Throughout this research the author successfully developed a methodology to identify potential maximum allowable task time for aircraft mechanical components/systems. This was performed based on existing methodology developed by Chipchak [14] which focused on electrical and electronic aircraft components/systems as there are very few elements of mechanical components/systems.

The validation process reported and described in this chapter and the following sections was implemented by using the process flow described and shown in Figure 6—1. Two case studies of aircraft landing gear for two aircraft BAe 146 and Jetstream 31 were used for the purpose of validation.

7.1 Validation 1 – BAe 146 – 300 – Landing Gear

7.1.1 **Introduction**

The validation process in this section is performed based on the author visit to approved MRO Company in UK. The BAe 146 – 300 is one of the aircraft available for author to study and visualise the aircraft components. Figure 7—1 show the pictures of BAe 146 – 300 aircraft landing gear used by author for the purpose of validation process.

Figure 7—1 BAe 146 – 300 aircraft landing gear (Source: Author)

7.1.2 **Service Difficulty Reports (SDR) - Landing Gear**

The first process was to understand the trend of SDR related to BAe 146. The historical data and information were analysed for a period of twenty years (1990 – 2009) and the results are shown in Table 7-1. BAe 146 SDR started from 1992 and increased up to 1998 with various types of part conditions. In total there are 1,688 SDR and the trend is illustrated in Figure 7—2.

The author decided to perform the SDR analysis up to twenty years because the data available for ten years (i.e. 2000 – 2009) are not enough for this research to make appropriate judgements. By extending the SDR analyses period this research should be able to understand and undertake necessary action to identify the most suitable aircraft mechanical components.

The results show increasing SDR reports in the first nine years (i.e. 1990 – 1998) however begins to decreasing in the following years beginning in 1999. This could be caused by the decrease in demand for this of type aircraft and/or the invention of new types of aircraft that could be more reliable and efficient.

Table 7-1 Summary of BAe 146 SDR Analyses

Year	Reported Difficulties Bae 146			TOTAL	%
	-100	-200	-300		
1990					
1991					
1992	1	6		7	0.41%
1993	1	43		44	2.61%
1994		14	3	17	1.01%
1995	74	113	57	244	14.45%
1996	11	150	47	208	12.32%
1997	8	124	192	324	19.19%
1998	48	250	85	383	22.69%
1999	18	144	17	179	10.60%
2000	15	93	11	119	7.05%
2001	12	43	19	74	4.38%
2002			12	12	0.71%
2003		14	10	24	1.42%
2004		9	22	31	1.84%
2005	2	5	9	16	0.95%
2006		3		3	0.18%
2007		3		3	0.18%
2008					
2009					
TOTAL	**190**	**1,014**	**484**	**1,688**	**100.00%**

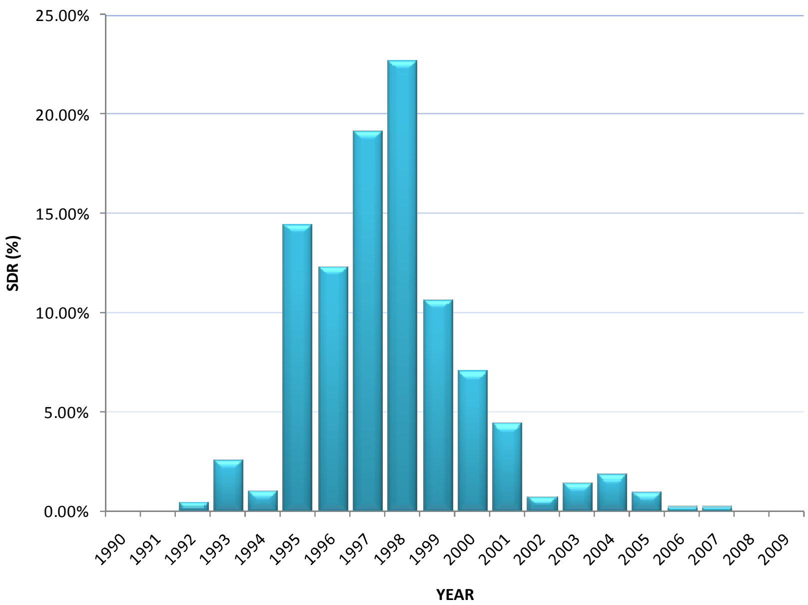


Figure 7—2 The trend of SDR analyses for all types of BAe 146

The first in the analysis is to identify which part name of the aircraft cause the greatest number of SDR. Figure 7—3 illustrates the percentage distribution of failed part condition for both BAe 146 – 200 and – 300. These two types of aircraft are chosen because they have contributed the highest SDR reports, as previously shown in Table 7-1. Landing gear has contributed the highest percentage of SDR reports with 18.18%, followed by Engine (Turbine/Turboprop) with 15.91%, and Flight Control System with 10.61%. as illustrate in Figure 7—3 with the total number of SDR for BAe 146 is 132.

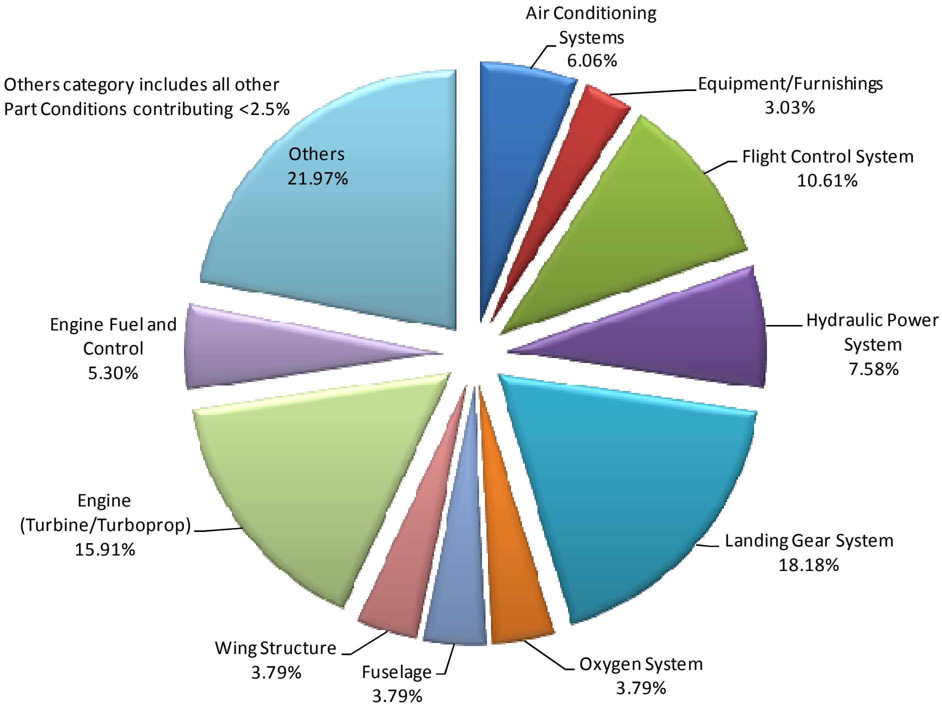


Figure 7—3 Failed Part Condition percentage distribution for BAe 146 in accordance with JASC Code

Because the Landing gear systems shows the highest contribution to SDR for BAe 146, the author carried out further analyses within Landing gear systems to have better understanding. There total of 100 SDR reports are collected for BAe 146 Landing gear system. Figure 7—4 illustrate the percentage distribution for BAe 146 Landing gear system in accordance with part conditions. The most reported part condition include cracked contributed 24.0% SDR reports, failed with 20.0% SDR reports, and corroded with 10.0% of SDR reports. Other types of part condition are faulty with 7.0 SDR reports and followed by damaged and broken which each one contributed 5.0% SDR reports.

In Table 7-2 show the detail SDR discrepancy statement which offer and useful to the designer to understand the scenario and condition why the components air failed.

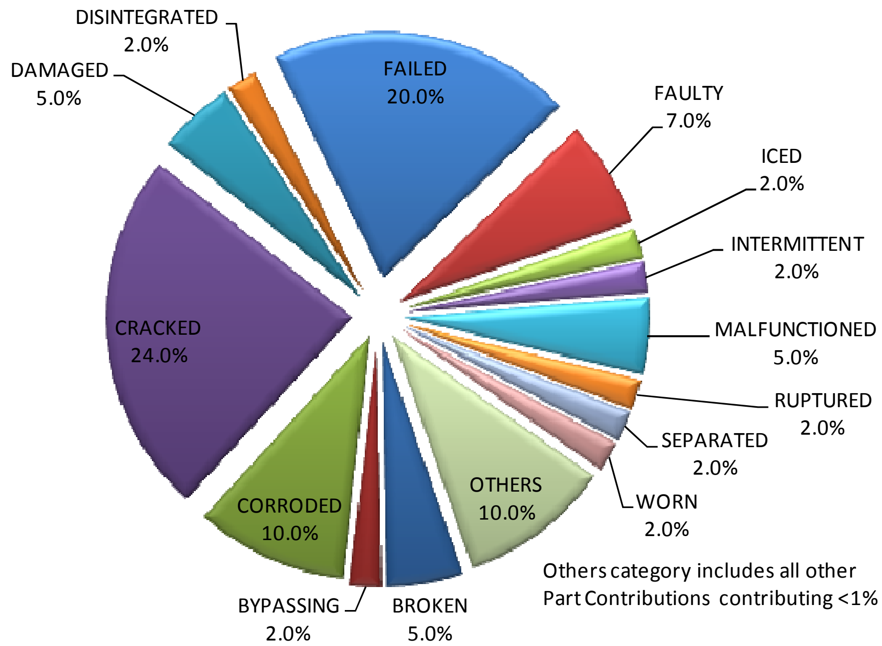


Figure 7—4 Percentage distribution for BAe 146 in accordance with Part Conditions

Table 7-2 Landing gear system SDR discrepancy statement in accordance with Part Condition [109]

JASCCo	PartCondition	PartLocation	Discrepancy
3260	FAILED	LT MLG	(AUS) LEFT MAIN LANDING GEAR UPLOCK ACTUATOR HOSE ASSEMBLY RUPTURED. HOSE LEAKING FROM END FITTING. LOSS OF `GREEN' SYSTEM HYDRAULICS.
3260	FAILED	RT MLG	LANDING GEAR HANDLE REQ OVERRIDE ON GEAR RETRACTION AFTER TAKEOFF FROM ORD. REMOVED AND REPLACED RIGHT MLG WEIGHT OFF HARNESS ASSY.
3230	FAILED	NLG	NOSE LANDING GEAR RETRACTION ACTUATOR FLEXIBLE HYDRAULIC HOSE RUPTURED. LOSS OF GREEN SYSTEM HYDRAULIC FLUID.
3297	FAILED	LT MLG DOOR	UPON GEAR RETRACTION LEFT MAIN GEAR SHOWS RED UNSAFE WITH GEAR HANDLE LT ON. REMOVED AND REPLACED LEFT MLG DOOR UPLOCK SENSOR HARNESS.
3234	FAILED	MLG	LANDING GEAR SELECTOR LEVER WOULD NOT MOVE TO THE `UP` POSITION.
3234	FAILED	LANDING GEAR	GEAR FAILED TO EXTEND WHEN SELECTED. WENT TO EMERGENCY AND GEAR EXTENDED. LANDED WITHOUT INCIDENT. SENT REPLACEMENT VALVE AND ACTUATOR TO DEN.

To have accurate understanding, the author carried out further analyses to identify which part name mostly affected and received the most SDR reports. Figure 7—5 illustrate the types of part name contributed the most SDR reports. Pin, actuator, and wheel contributed the most SDR reports which each one of the part name contributed 15.0% for pin, 8.0% for wheel, and 7.0% for actuator. In Table 7-3 shows the detail SDR discrepancy statement for BAe 146 Landing gear system in accordance with part name.

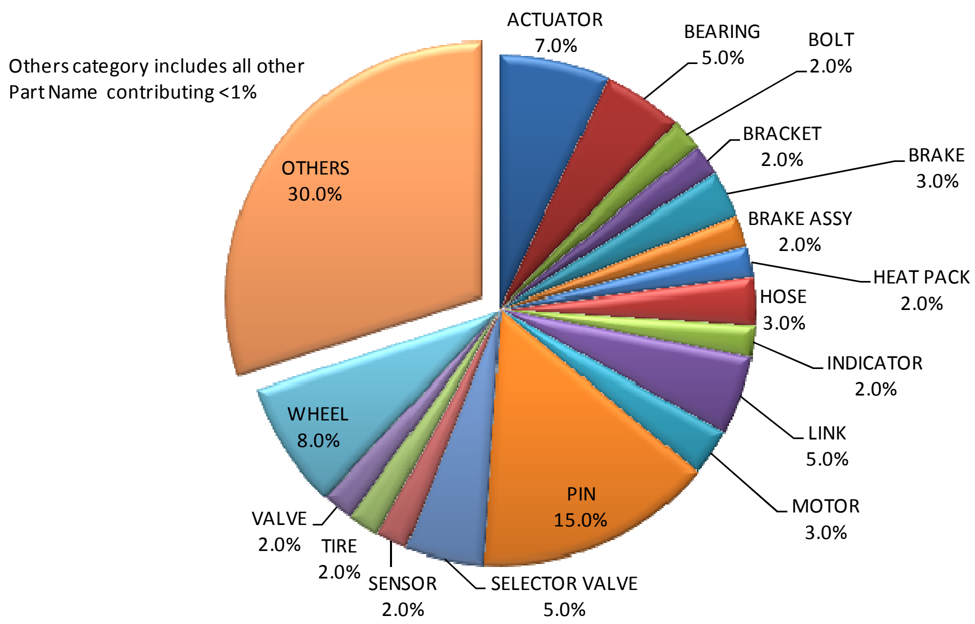


Figure 7—5 Percentage distribution for BAe 146 in accordance with Part Name

Table 7-3 Landing gear system SDR discrepancy statement in accordance with Part Name [109]

JASCCo	PartName	PartLocation	Discrepancy
3230	PIN	NLG	(AUS) NOSE LANDING GEAR RETRACTION JACK ATTACHMENT PIN CRACKED. FOUND DURING MAGNETIC PARTICLE INSPECTION. CRACK LENGTH 19.05 MM (0.75 INCH).
3230	PIN	NLG	(AUS) NOSE LANDING GEAR RETRACTION JACK ATTACHMENT PIN CRACKED. FOUND DURING MAGNETIC PARTICLE INSPECTION. CRACK LENGTHS 19.05 MM AND 12.7 MM.
3230	PIN	NLG	(AUS) NOSE LANDING GEAR RETRACTION JACK ATTACHMENT PIN CRACKED. FOUND DURING MAGNETIC PARTICLE INSPECTION. CRACK LENGTH 15.875 MM (0.625 INCH).
3230	PIN	NLG	(AUS) NOSE LANDING GEAR RETRACTION JACK ATTACHMENT PIN CRACKED. FOUND DURING MAGNETIC PARTICLE INSPECTION. CRACK LENGTH 76.2 MM (3 INCHES).
3213	PIN	MLG	(AUS) LT MAIN LANDING GEAR DIRECTIONAL LINK UPPER ATTACHMENT PIN FOUND TO BE MIGRATING FROM THE LUG LOCATED AT FRAME 29. LOCKING PLATE AND PIN INCORRECTLY FITTED. MAIN LANDING GEAR IS A NEWLYOVERHAULED UNIT AND HAD ONLY JUST BEEN FITTED TO THE AIRCRAFT 48CYCLES PREVIOUSLY.

Based on this result, the author found that the landing gear system is a part name for the validation process. Table 7-4 shows the list of information sources of how the validation process was performed.

Table 7-4 Summary of information sources for BAe 146 – 300 Landing Gear validation

No	Data and Information	Sources
1	List of Components	Approved Aircraft Maintenance Manual; and Analysed FAA Service Difficulty Reports [160]
2	List of Failure Rate	Non-electronic Part Reliability Data (NPRD) 1995 [155]
3	Mean Time to Failure (MTBF)	Equation 4-4
4	Maintainability Predictions	MIL-HDBK-472 [13]; DOD-HDBK-791 [62]; CAAIP [107]
5	Maintainability Prediction; Checklist C	Developed approach by author
6	Maintainability Allocation	Improved modules and scores by author
7	Process for Validation	As shown in Integrated Methodology, Chapter 6

7.1.3 **Maintainability allocation – BAe 146 – 300 Landing Gear**

Based on the methodology developed and described in chapter 4, the author's extended maintainability allocation method was used. The maintainability allocation was the next process to be performed, using extended modules and score values, by the author, as shown in Table 4-10. The maintainability allocation was predicted based on Mean Time to Repair (MTTR). The MTTR values can be predicted based on historical data, and/or the decision from top level management.

In this case study, the methodology developed as per described in Chapter 6 and shown in Figure 6—1. For the purpose of comparison, the author used two different approaches. One of the approaches is to utilise the 1.00 hour as an MTTR value as per advised by industrial experts. The result of the maintainability allocation is shown in Table 7-5.

Table 7-5 Maintainability allocation based on MTTR = 1.00

No	Components	Maintenance Allocation Time MTTR = 1.00 hour
1	ACTUATOR	0.85
2	ANTI SKID	0.85
3	BRAKE	1.32
4	BRAKE ASSY	1.08
5	CONNECTOR	0.85
6	CONTROL UNIT	0.75
7	HYDRAULIC	0.85
8	PROXIMITY SENSOR	1.13
9	PROXIMITY SWITCH	1.13
10	SELECTOR VALVE	0.85
11	SENSOR	0.94
12	STEERING	1.13
13	STRUCTURE	1.13
14	STRUT	1.13
15	SWITCH	0.85
16	TIRE	1.13
17	UPLOCK SWITCH	0.85
18	V-BELT	1.13
19	WARNING LIGHT	0.85
20	WARNING SYSTEM	1.13
21	WHEEL	1.13
22	WIRE	0.85
23	WIRE HARNESS	0.85

The rest of the prediction values were calculated by using the existing methodology developed by Chipchak [14] and by using new module and score improved by the author as shown in Table 4-10. There are some listed components requiring more than one module. Component number 4: Brake Assembly for example, required two modules, namely electromechanical equipment and mechanical structures, with mechanisms for which each module offered 3 and 8 score values respectively. Therefore allocation of the final score values for the brake assembly is by average, i.e. 5.5.

7.1.4 **Maintainability prediction – BAe 146 – Landing Gear**

The maintainability full scale prediction was begun with maintainability task time predictions by using MIL-HDBL-472, procedure III. The detailed process of task time predictions has been described in the maintainability prediction chapter. MIL-HDBK-472, procedure III consists of three main elements: Checklist A: Design; Checklist B; Facilities; and Checklist C: Human Factors. Maintainability prediction was performed by using checklists A and B questions.

To ensure the score values were accurately identified, additional references were used by the author such as Civil Aircraft Airworthiness Information and Procedure (CAAIP) or also known as CAP 562 and DoD-HDBK-791. Table 7-6 and Table 7-7 show the example of procedure statement used by author to understand the process of maintenance activities. The former was used in order to have better illustrations and DoD-HDBK-791 was used to understand the design criteria. The final result is shown in Table 7-8.

Table 7-6 Removal procedure for aircraft wheels. Source: CAAIP, CAP 562[107]

3.2.2 A typical removal procedure is described below:

a) Prepare aircraft for jacking in accordance with the appropriate aircraft Maintenance Manual.

b) Raise axle or bogie, as appropriate, until the tyre is clear of the ground.

c) Deflate tyre or reduce pressure to a low value.

NOTE: During release of tyre pressure, icing of the valve may occur and give a false indication of complete deflation. Sufficient time must elapse after the air flow has ceased to ensure that any ice has melted and that the tyre is sufficiently deflated.

d) Where applicable, remove cooling fan or hub cap assembly.

e) Remove axle nut locking device.

f) Remove axle nut and install thread protector.

g) Position wheel trolley and remove wheel carefully so as not to damage the axle.

NOTE: On some aircraft it is recommended that an approved extractor is used when removing the wheel.

h) Remove grease seals and bearings.

i) Install axle protector.

j) Fit protective cover over the brake assembly if the wheel is not to be re-fitted immediately.

Table 7-7 Installation procedure for wheels. Source: CAAIP, CAP 562[107]

3.4.2	**Installed Wheels** a) The wheel should be examined for cracks, corrosion, distortion, dents and scores, particular attention being given to the wheel flanges. Small dents on the outside of the flanges may usually be blended within specified limits, but in general no damage is permissible where the flange is in contact with the tyre. When a dent or abrasion is blended out, the exposed metal should be closely inspected for cracks and the protective treatment renewed. It is particularly important to give prompt attention to protective treatments following repairs to magnesium alloy wheels. b) Wheel hub tie bolts and nuts, inflation valves, balance weights and, where visible, the axle nut locking device, should be inspected for security and damage. If any tie bolt is found defective, the wheel should be removed and the complete set renewed. c) The wheel, brake and tyre should be examined for signs of overheating, such as blistered or discoloured paint, distortion and leakage of grease from the wheel bearings. **NOTE:** If a fusible plug is found to be blown out, the tyre should be scrapped and all fusible plug seals renewed, but the wheel may be satisfactory subject to certain checks (paragraph 3.4.3). d) Periodically the wheels should be raised clear of the ground in order to check for free rotation and end float in the bearings.

Table 7-8 Maintainability prediction tasks time for BAe 146 – 300 Landing Gear

No	Check List A: DESIGN	ACTUATOR	ANTI SKID	BRAKE	BRAKE ASSY	CONNECTOR	CONTROL UNIT	HYDRAULIC	PROXIMITY SENSOR	PROXIMITY SWITCH	SELECTOR VALVE	SENSOR	STEERING	STRUCTURE	STRUT	SWITCH	TIRE	UPLOCK SWITCH	V-BELT	WARNING LIGHT	WARNING SYSTEM	WHEEL	WIRE	WIRE HARNESS
	References: CAAIP																							
1	Access (External)	4	4	4	4	4	4	4	4	4	4	2	4	4	4	4	4	4	4	4	4	4	4	4
2	External lactches and/or fasterners	4	4	4	4	4	4	4	4	4	4	2	4	4	4	4	4	4	4	4	4	4	0	0
3	Internal latches and/or fastemers	4	4	4	4	4	4	4	4	4	4	2	4	4	4	4	4	4	4	4	4	4	0	0
4	Access (Internal)	4	4	4	4	4	4	4	4	4	4	2	4	4	4	4	4	4	4	4	4	4	4	4
5	Packaging	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Units - Part (Failed)	2	2	2	2	2	2	2	2	2	2	4	2	2	2	2	2	2	4	4	4	2	2	2
7	Visual Display	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
8	Fault and Operation Indicators (BITE)	2	2	2	2	2	2	2	4	4	2	4	2	2	2	2	2	2	2	4	4	2	2	2
9	Test Points (Availability)	2	2	2	2	2	2	2	2	2	2	2	2	4	4	2	3	2	2	2	2	4	4	4
10	Test Points (Identifications)	2	2	2	2	2	2	4	2	2	2	2	2	2	2		4	2	2	2	2	4	4	4
11	Labelling	4	4	4	4	2	4	4	4	4	0	4	4	4	4	4	4	4	4	4	4	4	4	4
12	Adjustments	2	2	2	2	4	4	2	2	4	4	4	4	4	2	4	4	4	4	4	4	4	4	4
13	Testing (In Circuit)	0	0	0	0	0	0	0	0	0	0	4	4	4	4	0	0	0	0	0	0	0	4	4
14	Protective Devices	2	2	0	0	0	2	2	2	2	4	2	4	4	4	4	2	2	2	2	2	4	4	4
15	Safety (Personnel)	2	2	2	2	4	4	2	4	4	4	4	2	4	4	4	4	4	4	4	4	2	4	4
		38	**38**	**36**	**36**	**38**	**42**	**40**	**42**	**44**	**40**	**42**	**46**	**50**	**48**	**42**	**45**	**42**	**44**	**46**	**46**	**46**	**44**	**44**

No	Check List B: FACILTIES	ACTUATOR	ANTI SKID	BRAKE	BRAKE ASSY	CONNECTOR	CONTROL UNIT	HYDRAULIC	PROXIMITY SENSOR	PROXIMITY SWITCH	SELECTOR VALVE	SENSOR	STEERING	STRUCTURE	STRUT	SWITCH	TIRE	UPLOCK SWITCH	V-BELT	WARNING LIGHT	WARNING SYSTEM	WHEEL	WIRE	WIRE HARNESS
1	External Test Equipment	1	1	2	2	4	2	1	2	2	4	2	2	2	2	4	4	4	4	4	4	4	2	2
2	Connectors	0	4	0	0	4	4	4	4	4	4	4	4	4	4	4	2	4	4	4	4	0	3	3
3	Jigs or Fixtures	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
4	Visual Contact	4	4	4	4	4	2	4	2	2	4	2	4	4	4	2	4	2	4	2	4	4	4	4
5	Assistance (Operational Personnel)	2	2	2	2	4	2	2	2	2	4	2	2	2	2	4	2	4	2	4	2	2	4	4
6	Assistance (Technical Personnel)	4	2	2	2	4	2	4	2	2	4	2	4	4	4	4	2	4	2	4	2	2	4	4
7	Assistance (Supervisor or Contractor Personnel)	4	4	4	4	4	2	4	2	2	4	2	4	4	4	4	4	4	2	4	2	4	4	4
		19	**21**	**18**	**18**	**28**	**18**	**23**	**18**	**18**	**28**	**18**	**24**	**24**	**24**	**26**	**22**	**26**	**22**	**26**	**22**	**20**	**25**	**25**

No	Check List C: Maintenance Skills (Human Factors)	ACTUATOR	ANTI SKID	BRAKE	BRAKE ASSY	CONNECTOR	CONTROL UNIT	HYDRAULIC	PROXIMITY SENSOR	PROXIMITY SWITCH	SELECTOR VALVE	SENSOR	STEERING	STRUCTURE	STRUT	SWITCH	TIRE	UPLOCK SWITCH	V-BELT	WARNING LIGHT	WARNING SYSTEM	WHEEL	WIRE	WIRE HARNESS
1	Arm, Leg, and Back Strength	4	2	4	4	4	3	4	3	4	4	4	4	4	4	4	2	4	3	4	4	2	4	4
2	Endurance and Energy	2	2	4	4	4	2	2	3	4	2	4	2	2	2	4	2	4	4	4	4	2	2	2
3	Eye-hand Coordination, Manual Dexterity and Neatness	0	2	4	4	4	3	2	3	4	2	3	2	2	2	4	2	4	4	4	4	2	3	3
4	Visual Acuity	2	2	4	4	4	3	2	3	3	2	4	2	2	2	3	2	3	3	3	3	2	3	3
5	Logical Analysis	1	2	4	4	4	3	1	3	3	1	4	2	0	0	3	2	3	3	3	3	2	3	3
6	Memory - Things and Ideas	2	4	4	4	4	3	2	3	3	2	4	2	2	2	3	2	3	3	3	3	4	3	3
7	Planfulness and Resourcefulness	2	2	4	4	4	3	2	3	4	2	3	2	2	2	4	2	4	4	4	4	2	4	4
8	Alertness, Cautiousness and Accuracy	0	4	3	3	4	3	2	3	3	2	4	0	0	0	3	2	3	3	3	3	4	3	3
9	Concentration, Persistence and Patience	0	2	4	4	4	3	2	3	3	2	4	0	0	0	3	2	3	3	3	3	2	3	3
10	Initiative and Incisiveness	2	2	4	4	4	3	2	3	3	2	4	2	0	0	3	2	3	3	3	3	2	3	3
		15	**24**	**39**	**39**	**40**	**29**	**21**	**30**	**34**	**21**	**38**	**18**	**14**	**14**	**34**	**20**	**34**	**33**	**34**	**34**	**24**	**31**	**31**
	Mct (Minutes)	70.40	48.76	46.35	46.35	19.92	42.13	40.69	41.08	33.09	28.63	33.59	28.91	25.37	28.48	21.16	33.53	21.16	25.61	16.79	22.25	32.94	21.81	21.81
	Mct (Hour)	1.17	0.81	0.77	0.77	0.33	0.70	0.68	0.25	0.55	0.48	0.56	0.48	0.42	0.47	0.35	0.56	0.35	0.43	0.28	0.37	0.55	0.36	0.36

Average (Minutes) 32.64

Average (hours) 0.53

7.1.5 **Process validation**

In this section, the author described the second stage of maintainability allocation process. In this stage a more accurate MTTR value is used based on the maintainability prediction results to check the allocation method. The process is carried out in accordance with Figure 6—1.

The second stage utilises the MTTR calculated from the maintainability prediction results above shown in Table 7-8. In addition, the second stage is utilised for the purpose of comparison as to identify the accuracy of prediction. The result of the maintainability allocation is shown in Table 7-9.

Table 7-9 Maintainability Allocation base on MTTR= 0.53

No	Components	Maintenance Allocation Time MTTR = 0.53 hour
1	ACTUATOR	0.45
2	ANTI SKID	0.45
3	BRAKE	0.70
4	BRAKE ASSY	0.57
5	CONNECTOR	0.45
6	CONTROL UNIT	0.40
7	HYDRAULIC	0.45
8	PROXIMITY SENSOR	0.60
9	PROXIMITY SWITCH	0.60
10	SELECTOR VALVE	0.45
11	SENSOR	0.50
12	STEERING	0.60
13	STRUCTURE	0.60
14	STRUT	0.60
15	SWITCH	0.45
16	TIRE	0.60
17	UPLOCK SWITCH	0.45
18	V-BELT	0.60
19	WARNING LIGHT	0.45
20	WARNING SYSTEM	0.60
21	WHEEL	0.60
22	WIRE	0.45
23	WIRE HARNESS	0.45

The list of components as collected from the SDR analyses. All listed components are received the most reports of SDR. As results, Table 7-10 show the summary for both MTTR values and both results are illustrated in Figure 7—6. Both MTTR show almost the same trendlines. The detail of the maintenance allocation is also shown in Appendix J.

Table 7-10 The summary of maintainability allocation for BAe 146 – 300 for both MTTR values.

No	Components	Maintenance Allocation Time in hour	
		MTTR = 1.00 hour	MTTR = 0.53 hour
1	ACTUATOR	0.85	0.45
2	ANTI SKID	0.85	0.45
3	BRAKE	1.32	0.70
4	BRAKE ASSY	1.08	0.57
5	CONNECTOR	0.85	0.45
6	CONTROL UNIT	0.75	0.40
7	HYDRAULIC	0.85	0.45
8	PROXIMITY SENSOR	1.13	0.60
9	PROXIMITY SWITCH	1.13	0.60
10	SELECTOR VALVE	0.85	0.45
11	SENSOR	0.94	0.50
12	STEERING	1.13	0.60
13	STRUCTURE	1.13	0.60
14	STRUT	1.13	0.60
15	SWITCH	0.85	0.45
16	TIRE	1.13	0.60
17	UPLOCK SWITCH	0.85	0.45
18	V-BELT	1.13	0.60
19	WARNING LIGHT	0.85	0.45
20	WARNING SYSTEM	1.13	0.60
21	WHEEL	1.13	0.60
22	WIRE	0.85	0.45
23	WIRE HARNESS	0.85	0.45

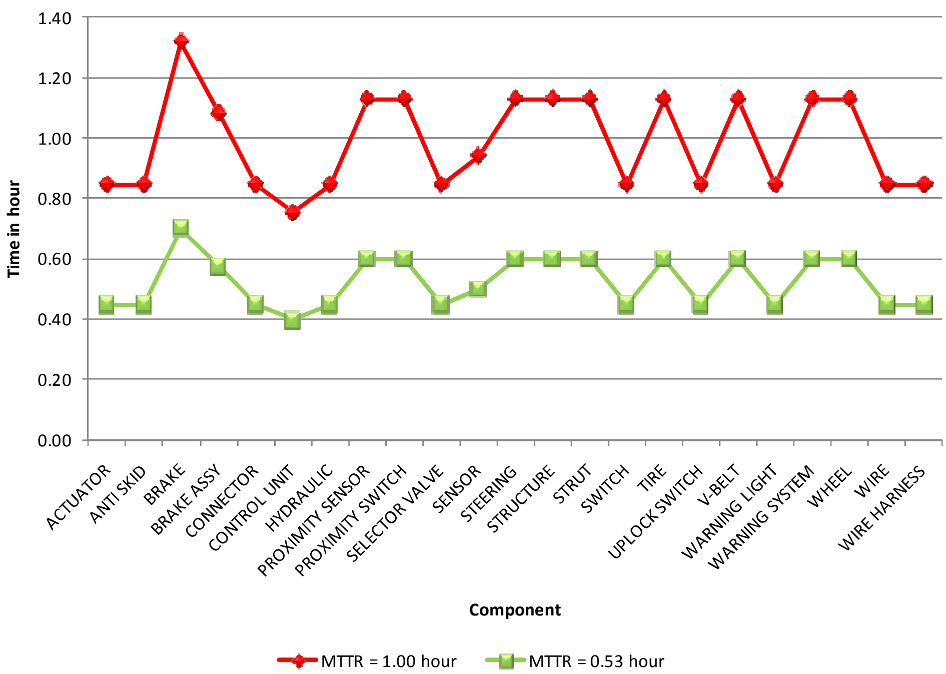


Figure 7—6 The trend of maintainability allocation times for both MTTR values for BAe 146 – 300 Landing Gear

7.1.6 **Summary – Validation 1**

There are two scenarios of results from this validation. Table 7-11 shows the summary for both maintenance allocation time and maintainability prediction. Meanwhile Figure 7—7 illustrated the summary results. Collectively, the results indicate that the MTTR 1.00 hour shows the better results compare MTTR 0.53 hour.

By using MTTR 1.00 hour all components appear within and acceptable maintainability criteria where only one component need to re-examined for the maintainability prediction time. In MTTR 0.53 hour which is the value of average from the maintainability prediction time shows six components need to consider for maintainability re examination at the same time approximately 74% (17 components) are appear within maintainability acceptable range.

Therefore, if the designer and maintainability evaluator focusing on simplify the design in order to have minimum task time as possible, therefore the MTTR value of 0.53 hour is the best answer.

Table 7-11 The summary of maintainability allocation and prediction tasks time for BAe 146 – 300 for both MTTR values.

No	Components	Maintainability Prediction Time (Hour)	Maintainability Allocation Time (hour)		Decision	
			MTTR = 1.00	MTTR = 0.53	MTTR = 1.00	MTTR = 0.53
1	ACTUATOR	0.76	0.85	0.45	GOOD	NOT GOOD
2	ANTI SKID	0.36	0.85	0.45	GOOD	GOOD
3	BRAKE	0.67	1.32	0.70	GOOD	GOOD
4	BRAKE ASSY	0.67	1.08	0.57	GOOD	NOT GOOD
5	CONNECTOR	0.34	0.85	0.45	GOOD	GOOD
6	CONTROL UNIT	0.78	0.75	0.40	NOT GOOD	NOT GOOD
7	HYDRAULIC	0.61	0.85	0.45	GOOD	NOT GOOD
8	PROXIMITY SENSOR	0.55	1.13	0.60	GOOD	GOOD
9	PROXIMITY SWITCH	0.28	1.13	0.60	GOOD	GOOD
10	SELECTOR VALVE	0.36	0.85	0.45	GOOD	GOOD
11	SENSOR	0.55	0.94	0.50	GOOD	NOT GOOD
12	STEERING	0.52	1.13	0.60	GOOD	GOOD
13	STRUCTURE	0.41	1.13	0.60	GOOD	GOOD
14	STRUT	0.41	1.13	0.60	GOOD	GOOD
15	SWITCH	0.31	0.85	0.45	GOOD	GOOD
16	TIRE	0.56	1.13	0.60	GOOD	GOOD
17	UPLOCK SWITCH	0.54	0.85	0.45	GOOD	NOT GOOD
18	V-BELT	0.52	1.13	0.60	GOOD	GOOD
19	WARNING LIGHT	0.25	0.85	0.45	GOOD	GOOD
20	WARNING SYSTEM	0.34	1.13	0.60	GOOD	GOOD
21	WHEEL	0.59	1.13	0.60	GOOD	GOOD
22	WIRE	0.30	0.85	0.45	GOOD	GOOD
23	WIRE HARNESS	0.30	0.85	0.45	GOOD	GOOD
	Average	0.48			22	17

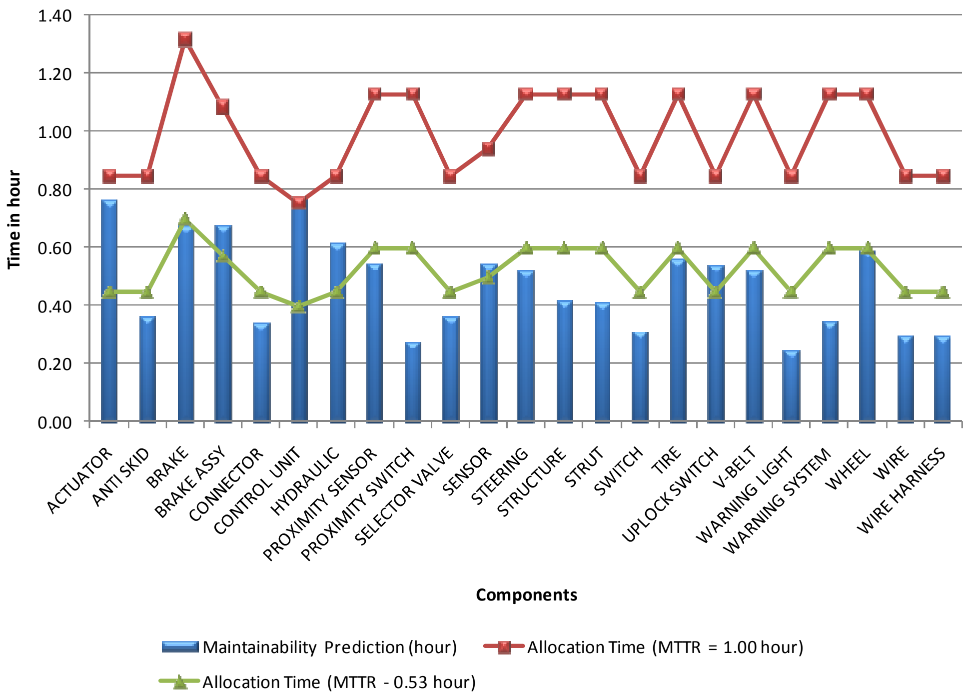


Figure 7—7 The trend of maintainability prediction and allocation times for both MTTR values for BAe 146 – 300 Landing Gear

7.2 Validation 2 – Jetstream 31 – Landing Gear

7.2.1 **Introduction**

This second validation process was from aircraft Jetstream 31. This aircraft is owned by Cranfield University and maintained by certified personnel. There were two main components involved: Nose Landing Gear (NLG) as shown in Figure 7—8 and Main Landing Gear (MLG) as shown in Figure 7—10. Other component includes the uplock assembly as shown in Figure 7—9.

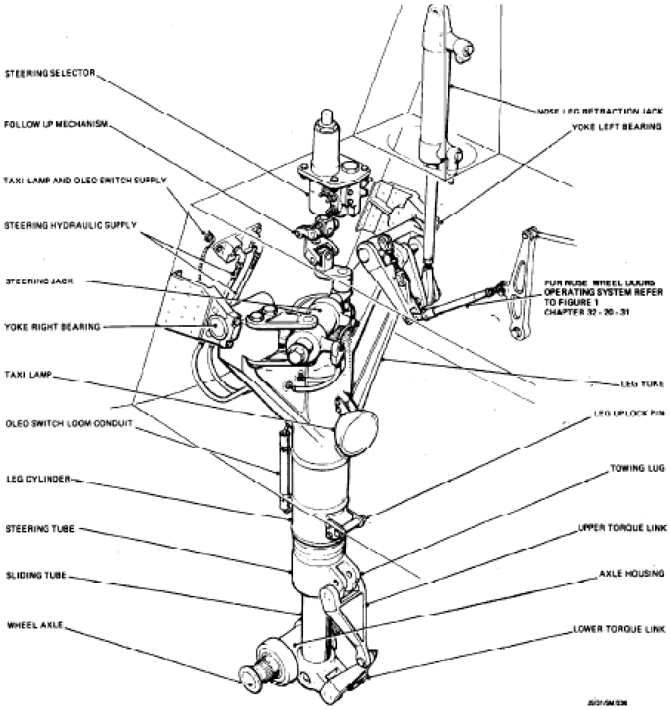


Figure 7—8 Jetstream 31 Nose Landing Gear (Source: Cranfield University)

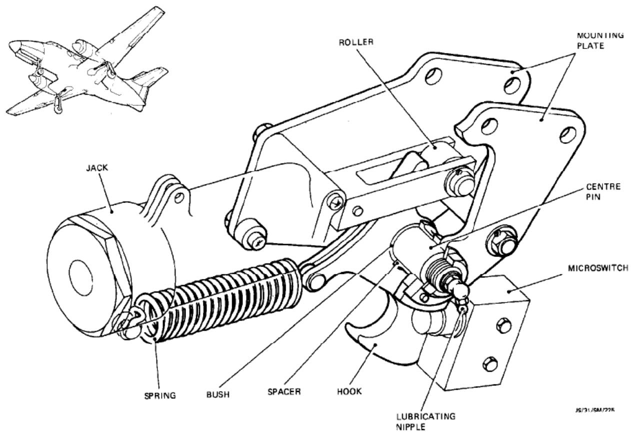


Figure 7—9 Jetstream 31 Uplock Assembly (Source: Cranfield University)

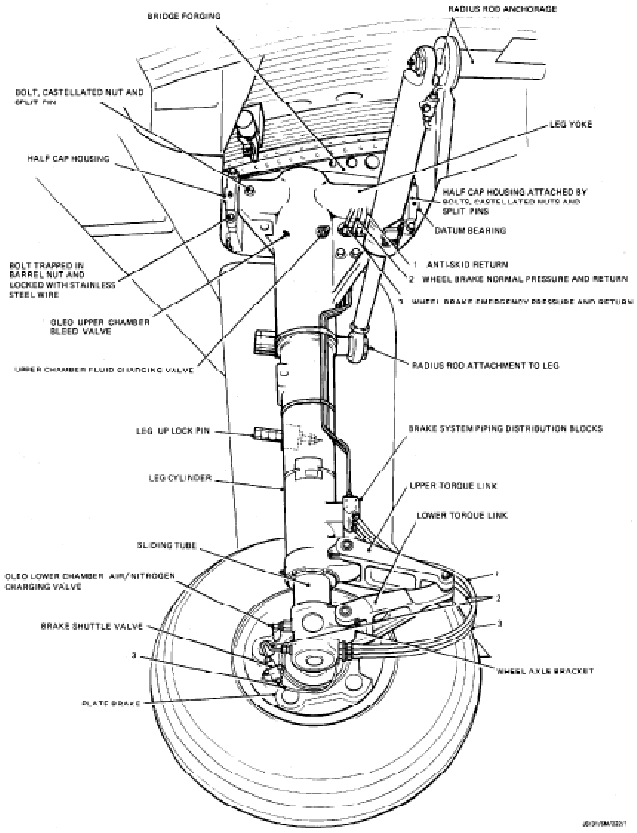


Figure 7—10 Jetstream 31 Main Landing Gear (Source: Cranfield University)

Table 7-12 Summary of information sources for Jetstream 31 Landing Gear validation

No	Data and Information	Sources
1	List of Components	Approved Aircraft Maintenance Manual;
2	List of Failure Rate	Non-electronic Part Reliability Data (NPRD) 2011[152]
3	Mean Time to Failure (MTBF)	Equation 4-4
4	Maintainability Predictions	MIL-HDBK-472 [13]; DOD-HDBK-791 [62]; CAAIP [107], & Approved Aircraft Maintenance Manual
5	Maintainability Prediction; Checklist C	Developed approach by author
6	Maintainability Allocation	Improved modules and scores by author
7	Process for Validation	As shown in Integrated Methodology, Chapter 6

The main focus was to perform the validation by using the proposed research methodology, as shown in Figure 6—1 and compare the validation task time with the real task time supplied by Jetstream 31. The validation also included the use of improved techniques by the author in MIL-HDBK-472, Procedure III, checklist C Human Factor and described specifically in section 3.3.3.

Based on SDR analyses, the Jetstream 31 Landing Gear has contributed the most service difficulties since 2000. The detail of SDR analyses is described in the following section.

7.2.2 **Service Difficulty Reports (SDR) – Jetstream 31 Landing Gear**

The first process was to understand the trend of SDR related to Jetstream. The historical data and information were analysed for a period of ten years (2000 – 2009) and the results are shown in Table 7-13 and illustrated in Figure 7—11. There have been 1,411 SDR for all Jetstream aircrafts since 2000. The results show a decreasing trend of SDR starting in 2004 and this could be as a result of the popularity of this type of aircraft. Other models have been included to provide a larger database.

Table 7-13 Summary of Jetstream SDR analyses

Jetstream	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL
31	20	5	19	13	10	6	8	4	1		86
32	71	49	19	7	4	5	3		2		160
41	145	123	259	274	184	144	36				1,165
TOTAL	**236**	**177**	**297**	**294**	**198**	**155**	**47**	**4**	**3**	**0**	**1,411**

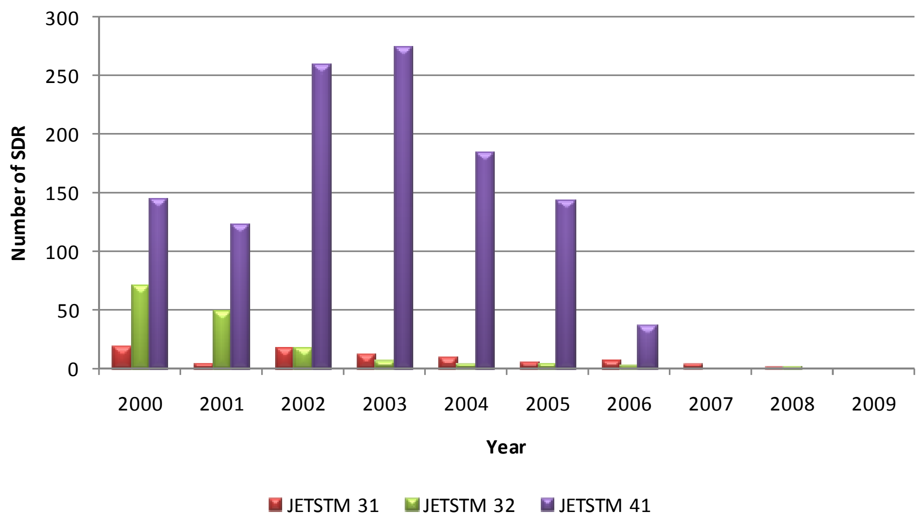


Figure 7—11 The trend of SDR analyses fro all types of Jetstream

The following process of SDR analyses is to review and understand the trend of SDR part condition. This is to view the most reported type of part conditions for Jetstream 31 and the results are shown in Figure 7—12 the top ten JASC code and part name. The most reported SDR in according JASC code and part name are JASC code 34 Navigation with 16.84%, JASC code 32 Landing Gear with 12.03%, and JASC code JASC code 24 Electrical Power with 11.68%.

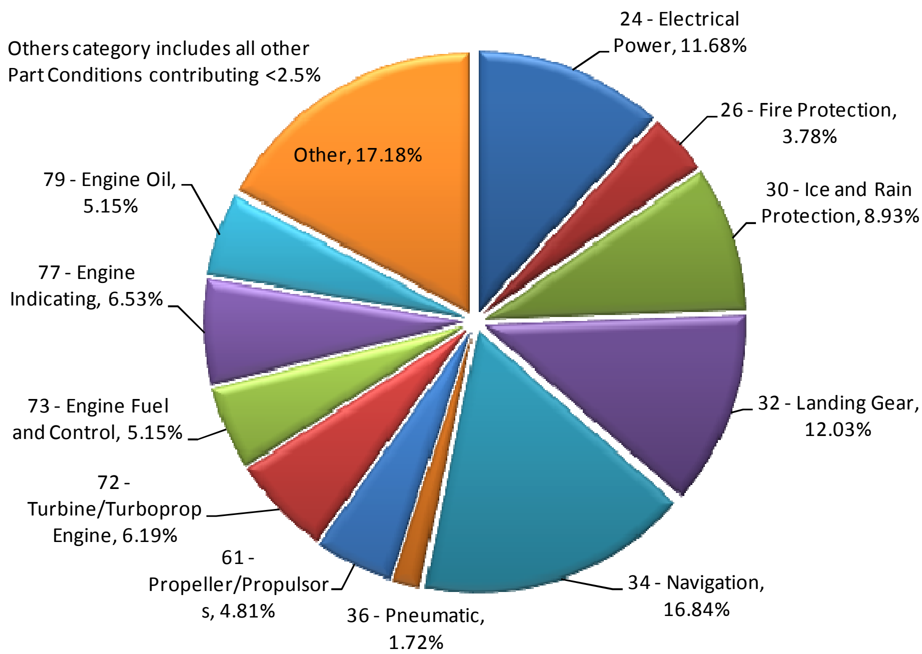


Figure 7—12 Failed Part Condition percentage distribution for Jetstream in accordance with JASC Code

Meanwhile, Figure 7—13 shows the top ten types of part conditions. Table 7-16 shows the detail data collected and it can be seen that the year 2000 contributed the most SDR reports. This could be because Jetstream were manufacture from 1969 to 1997, and therefore by the year 2000 there were still many aircraft in service by they were now no new aircraft being produced.

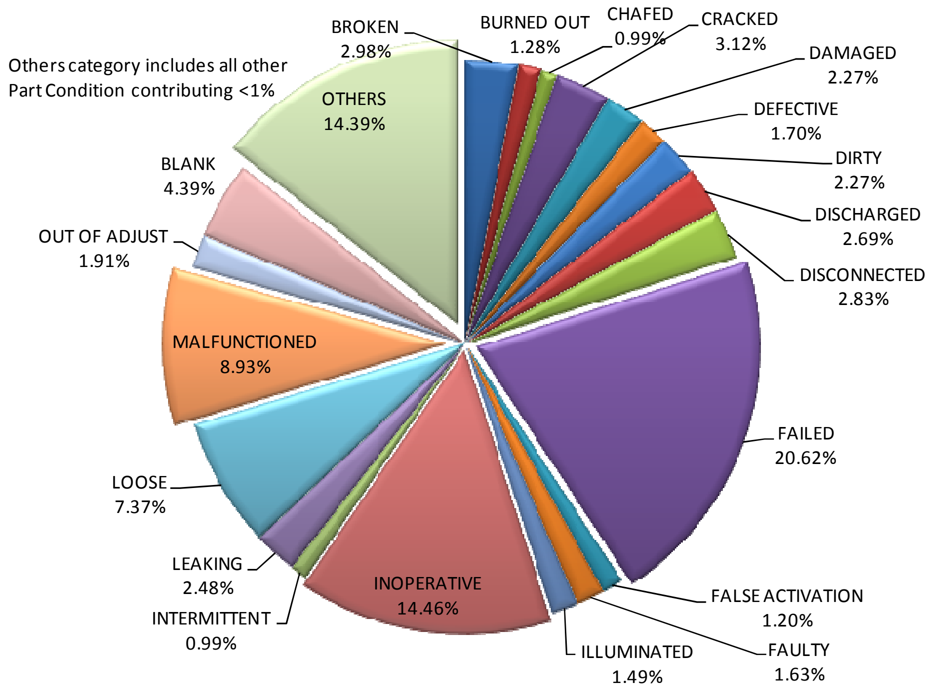


Figure 7—13 Part Condition percentage distribution for all Jetstream models

Table 7-14 Landing gear system SDR discrepancy statement in accordance with Part Condition for failed part condition [109]

JASC CODE	AIRCRAFT COMPONENT	PART CONDITION	DISCREPANCY
3250	NLG STEERING	FAILED	7301-DEC- DURING TAXI OUT NOSE WHEEL STEERING WOULD NOT TURN RIGHT. MAINTENANCE REMOVED AND REPLACED THE STEERING SELEC
3250	NLG STEERING	FAILED	7301-DEC- DURING TAXI OUT NOSE WHEEL STEERING WOULD NOT TURN TO THE RIGHT. MAINTENANCE REMOVED AND REPLACED THE STEERING CABLE IAW J41 MAINTENANCE MANUAL
3260	NLG	FAILED	5382-RIC- DURING FLIGHT NOSE LANDING GEAR INTRANSIT LIGHT INOP. MAINTENANCE REMOVED AND REPLACED THE NOSE LANDING GEAR MICRO SCITCH IAW J41 MAINTENANCE MANUAL
3241	NR 4 WHEEL	FAILED	STL-DURING TAXI ANTI-SKID CAPTION LIGHT ILLUMINATED. MAINTENANCE REMOVED AND REPLACED NR 4 ANTI-SKID WHEEL SPEED TRANSDUCER IAW J41 MAINTENANCE MANUAL
3241	ANTI- SKID	FAILED	5358-EWR-DURING TAXI IN LEFT HAND MAIN LANDING GEAR BRAKES LOCKED UP DUE TO ANTI-SKID FAILURE NR 1 MAIN TIRE IS FLAT. MAINTENANCE REMOVED AN REPLACED NR 1 AND 2 MAIN LANDING GEAR TIRE IAW J41 MAINTENANCE MANUAL.
3242	BRAKE SYS	FAILED	9549-ROC-AIRCRAFT PULLED TO THE LEFT AS IF LEFT HAND MAIN LANDING GEAR TIRES LOCKED UP, AIRCRAFT WAS UNABLE TO TAXI. MAINTENANCE REMOVED AND REPLACED THE DUAL BRAKE CONTROL VALVE IAW J41 MAINTENANCE MANUAL.
3241	ANTI-SKID	FAILED	5358-EWR-DURING TAXI IN LEFT HAND MAIN LANDING GEAR BRAKES LOCKED UP DUE TO ANTI SKID FAILURE NR 2 MAIN TIRE WAS FLAT. MAINTENANCE REMOVED AND REPLACED NR 2 MAIN LANDING GEAR TIRE IAW J41 MAINTENANCE MANUAL.
3230	L/H MLG	FAILED	7412-STL-LANDING GEAR WOULD NOT RETRACT AFTER TAKEOFF. MAINTENANCE INSPECTED AND REPLACED LEFT MAIN LANDING GEAR RETRACT ACTUATOR
3230	INST PNL	FAILED	7439-CMI-UPON APPROACH NORMAL LANDING GEAR EXTENSION WAS INOPERATIVE, CREW PERFORMED EMERGENCY GEAR EXTENSION AND LANDED WITHOUT INCEDENT. MAINTENANCE INSPECTED AND REPLACED INSTRUMENT PANEL LANDING GEAR HANDLE, PERFORMED OPERATIONAL CHECK

Table 7-15 Landing gear system SDR discrepancy statement in accordance with Part Condition for malfunctioned part condition [109]

JASC CODE	AIRCRAFT COMPONENT	PART CONDITION	DISCREPANCY
3200	MLG	MALFUNCTIONED	LANDING GEAR INTRANSIT LIGHT STAYED ON LT. COULD NOT DUPLICATE. PRECAUTIONARY REPLACEMENT OF UPLOCK AND DOWNLOCK SWITCHES PER SB32-891142, PERFORMED ON LEFT MAIN GEAR. (M)
3210	L/H MLG	MALFUNCTIONED	7306-STL- DURING CLIMBOUT ALL LANDING GEAR WOULD NOT RETRACT. MAINTENANCE REMOVED AND REPLACED LEFT HAND MAIN LANDING GEAR IAW J41 MAINTENANCE MANUAL
3230	MLG	MALFUNCTIONED	GEAR WOULD NOT RETRACT AFTER TAKEOFF. NO EMERGENCY DECLARED RETURN TO FIELD. JACKED AIRCRAFT RESET MAIN LANDING GEAR BYPASS PIN OPERATIONALLY CHECKED LANDING GEAR. NO FURTHER ACTION REQUIRED.

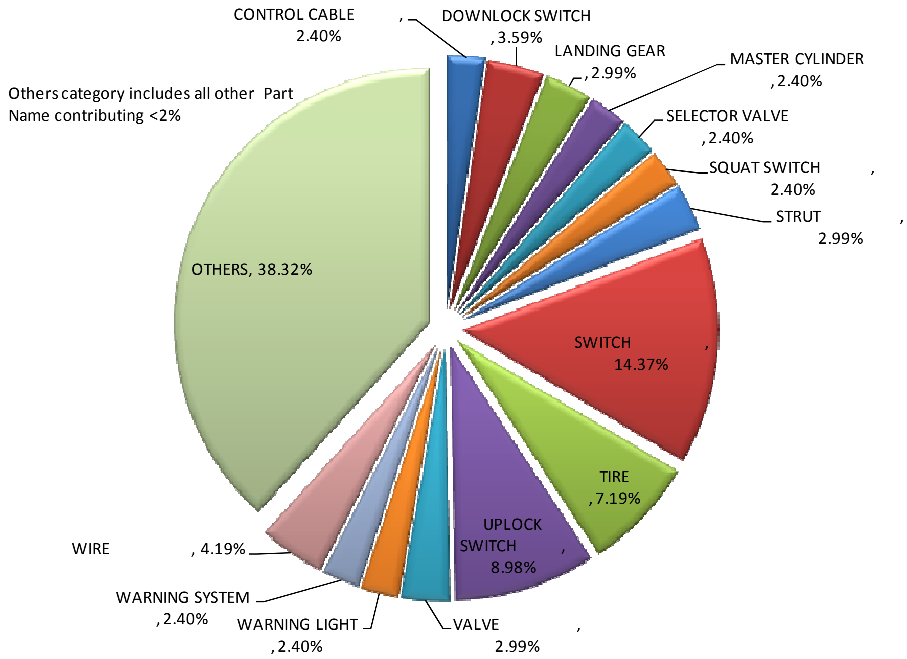


Figure 7—14 Percentage distribution for Jetstream in accordance with Part Name

Table 7-16 The detailed report of the part condition for all Jetstream models

NO	PART CONDITION	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%
1	BROKEN	2	6	14	9	2	6	3				42	2.98%
2	BURNED OUT			2	13	3						18	1.28%
3	CHAFED	3	2	3	3	2	1					14	0.99%
4	CRACKED	14	4	3	11	8	2	2				44	3.12%
5	DAMAGED	5	5	3	6	6	3	3		1		32	2.27%
6	DEFECTIVE		6	5	7	6						24	1.70%
7	DIRTY	2	3	5	6	1	12	3				32	2.27%
8	DISCHARGED	2	4	8	14	7		3				38	2.69%
9	DISCONNECTED	1	7	16	11	3	2					40	2.83%
10	FAILED	152	64	16	21	19	19					291	20.62%
11	FALSE ACTIVATION		1	10		3	2	1				17	1.20%
12	FAULTY	2		3	8	4	4	2				23	1.63%
13	ILLUMINATED	1		1	6	6	7					21	1.49%
14	INOPERATIVE		11	54	70	36	28	4	1			204	14.46%
15	INTERMITTENT	1		6	3	2	1	1				14	0.99%
16	LEAKING	7	5	9	6	5	2		1			35	2.48%
17	LOOSE	2	5	39	32	8	10	7		1		104	7.37%
18	MALFUNCTIONED	8	11	9	20	45	29	4				126	8.93%
19	OUT OF ADJUST	3	7	5	3	2	6	1				27	1.91%
20	BLANK		6	47	9							62	4.39%
21	OTHERS											203	14.39%
	TOTAL	205	147	258	258	168	134	34	2	2	0	**1,411**	**100.00%**

7.2.3 **Maintainability allocation – Jetstream 31 Landing Gear**

The maintainability allocation prediction was performed to identify the maximum target of maintenance task time for each individual component. It used improved modules, as previously described in chapter 4, and the results are shown in Table 7-17 and illustrated in Figure 7—15. The lists of components are the components that are suggested by industrial expert and both MTTR show almost the same trendlines.

Table 7-17 The summary of maintainability allocation for Jetstream 31 both MTTR values

No	Components	Maintainability Allocation Time (hour)	
		MTTR = 1.00	MTTR = 3.76
1	Main Gear Uplock Assembly	0.51	1.90
2	Main Landing Gear Radius Rod	0.72	2.71
3	Main Landing Gear	1.01	3.80
4	Nose Gear Uplock Assembly	0.51	1.90
5	Nose Landing Gear	1.01	3.80

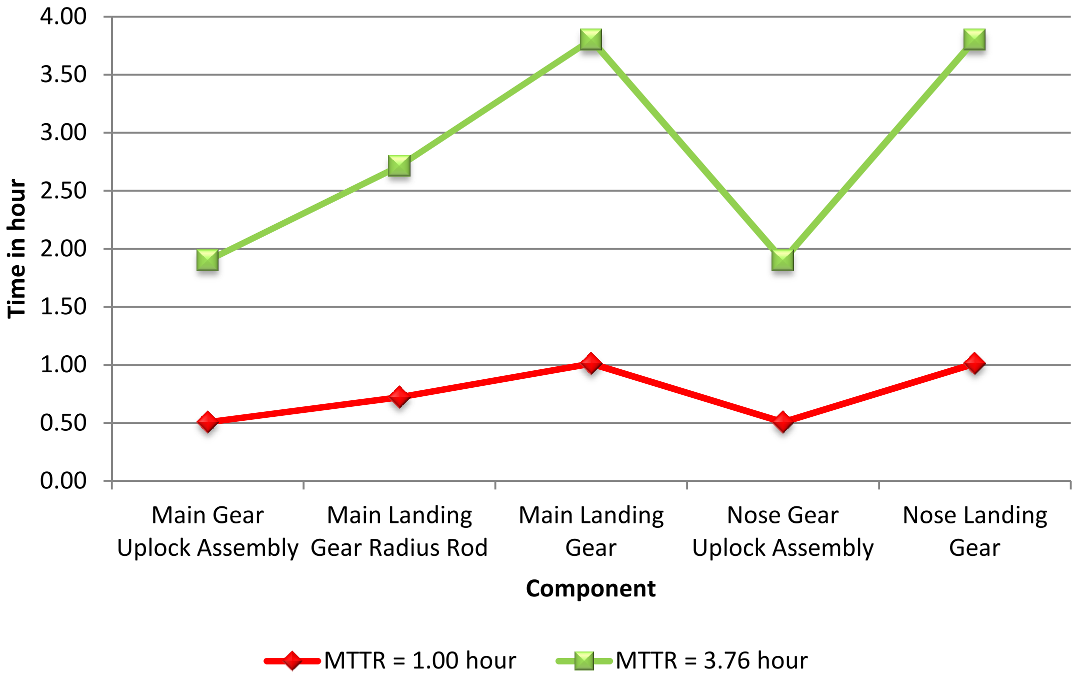


Figure 7—15 The trend of maintainability allocation times for both MTTR values for Jetstream 31 Landing Gear

7.2.4 Maintainability prediction – Jetstream 31 Landing Gear

Based on SDR analyses described in section 7.2.2, the author decided to use Jetstream 31 landing gear as a case study for the validation process. The process of maintainability prediction is carried out by using approved aircraft maintenance manual provided by MRO company as shown in Table 7-12.

Table 7-18 shows the summary of validation results. The real time column is the task time supplied by Jetstream 31. The real task time includes the time for the functional test. However, in this research the methodology was developed to predict the task time for removal and replace (R & R) only. The detail maintainability prediction for Jetstream 31 landing gear is shown in Appendix K, and the maintenance analysis for all components is given in Appendix L.

Table 7-18 The summary of maintainability results for Jetstream 31 Landing Gear

A	B	C	D	E	F	G	H	I	J
No	Component Name	Qty	Billing Time	Manhour R & R	Functional Test (30%) in hour	Marginal Time (10%) in hour	GRAND TOTAL (hour)	Error (hour)	% (Column I/ H)
1	Main Gear Uplock Assembly	2	3.0	1.26	0.90	0.30	2.46	0.54	22.05%
2	Main Landing Gear Radius Rod	2	3.0	1.18	0.90	0.30	2.38	0.62	26.07%
3	Main Landing Gear	2	14.0	6.46	4.20	1.40	12.06	1.94	16.12%
4	Nose Gear Uplock Assembly	1	3.0	1.54	0.90	0.30	2.74	0.26	9.61%
5	Nose Landing Gear	1	14.0	8.35	4.20	1.40	13.95	0.05	0.36%
			Average	3.76					

Note:
The Functional Tests were **NOT** included in this predictions;
Assuming Functional Test = 30% from real time;
Assuming Marginal Time = 10% from real time;
Industrial Info 1: Functional test only performed every 4 years.
R & R = Remove and Replace

The real time mentioned above is also known as “billing” time from approved MRO to customer. By using MIL-HDBK-472, procedure III and improved checklist C, the predicted man-hour for each component is 1.26 hours for Main Gear Uplock Assembly, 1.18 hours for MLG radius rod, 6.46 hours for MLG, 1.54 hours for Nose Gear Uplock Assembly, and 8.35 hours for NLG. The man-hours for NLG are more than other landing gear components because NLG is the most difficult task compared to MLG and this has been confirmed by a Jetstream engineer.

“Grand Total” column is the total prediction hour by this research which is calculated by add column E, column, F, and column G. In “Error” column (Column I) calculated by subtracting the Grand total value (Column H) from billing time (Colum D). This is to see either the predicted values from this research are matching with industrial real time. As a result, MLG Radius Rod contributed 26.07% less than real billing time (column C). Mean while Main Gear Uplock Assembly contributed 22.05% less real billing time. During design review process or maintainability improvement process those two components (MLG Radius Rod & Main Gear Uplock Assembly) needs to be considered for redesign. This may include simplifying the design or specification improvement. However, this research is a success because the improved checklist C from MIL-HDBK-472, procedure III has been tested and validation by using real industrial time and shows good results.

The only reference provided by the industry is known as "billing time". Billing time is the time charged to the customer which most of the times include extra time for contingency. Based on billing time that is provided by the industry, overall validation evaluation is successful. It is because all the predicted values fall within real industrial time as shown in Table 7-18 and Figure 7—16. Therefore, based on billing time provided by the industry, this research confirms that the developed methodology is viable and useful based on available data. However, the actual maintenance task time may differ from the billing time data used in the validation. As such, a more robust validation may be pursued in the future by collecting actual maintenance task time, in addition to the billing time.

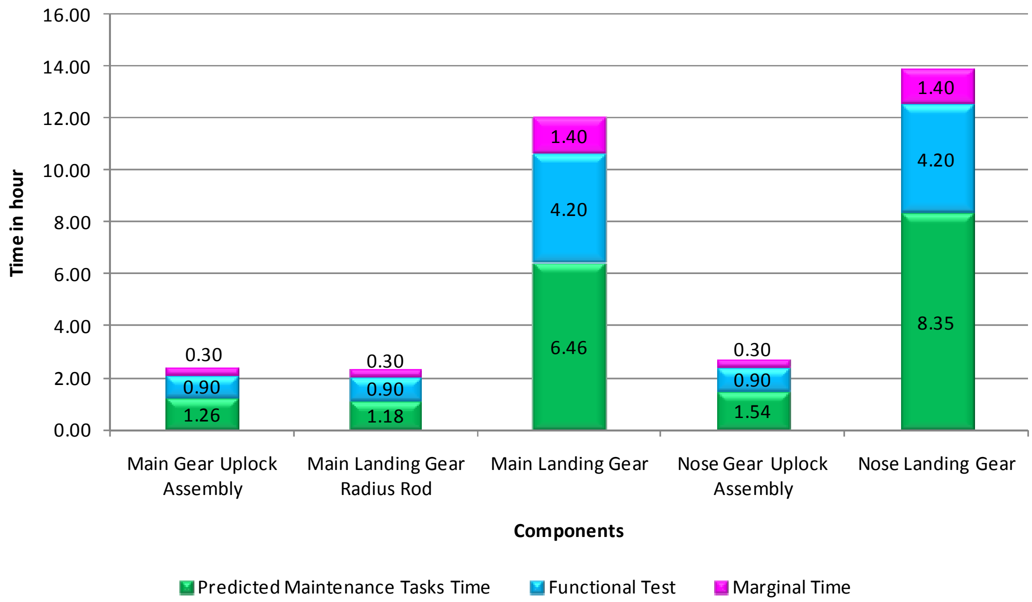


Figure 7—16 Summary of Maintainability Predicted Tasks Time for Jetstream 31

Table 7-19 Maintainability prediction tasks time for Jetstream 31 Landing Gear

	Components	MLG Uplock		MAIN LANDING GEAR							NLG Uplock		NOSE LANDING GEAR						
	Check List A: DESIGN	Uplock	Uplock Jack	Radius Rod	Main Gear Leg	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy	Uplock	Uplock Jack	Nose Leg Retraction Jack	Leg Cylinder	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy
1	Access (External)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	External lactches and/or fasterners	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	Internal latches and/or fasterners	4	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	Access (Internal)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	Packaging	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Units - Part (Failed)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	Visual Display	2	2	4	4	4	4	4	4	4	2	2	0	4	4	4	4	4	4
8	Fault and Operation Indicators (BITE)	2	2	3	4	3	3	3	3	3	2	2	3	4	3	3	3	3	3
9	Test Points (Availability)	4	4	3	3	3	3	3	3	3	4	4	3	3	3	3	3	3	3
10	Test Points (Identifications)	0	0	2	2	2	2	2	2	2	0	0	2	2	2	2	2	2	2
11	Labelling	0	0	2	4	4	2	4	4	4	2	2	2	4	4	2	4	4	4
12	Adjustments	2	2	2	2	4	4	2	2	2	2	2	2	2	4	4	2	2	2
13	Testing (In Circuit)	4	4	4	4	4	4	4	4	4	4	4	2	2	4	4	4	4	4
14	Protective Devices	0	0	2	2	2	2	2	0	0	0	0	2	2	2	2	2	0	0
15	Safety (Personnel)	4	4	2	4	4	4	4	4	4	2	4	2	4	4	4	4	4	4
	TOTAL	**30**	**30**	**34**	**39**	**40**	**38**	**38**	**36**	**36**	**28**	**30**	**28**	**37**	**40**	**38**	**38**	**36**	**36**
	Check List B: FACILTIES	Uplock	Uplock Jack	Radius Rod	Main Gear Leg	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy	Uplock	Uplock Jack	Nose Leg Retraction Jack	Leg Cylinder	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy
1	External Test Equipment	4	4	4	2	4	4	4	4	4	4	4	4	2	4	4	4	4	4
2	Connectors	4	4	4	2	4	4	4	4	4	4	4	4	2	4	4	4	4	4
3	Jigs or Fixtures	4	4	4	0	4	2	4	2	2	4	4	4	0	4	2	4	2	2
4	Visual Contact	4	4	2	4	4	4	4	4	4	2	2	2	4	4	4	4	4	4
5	Assistance (Operational Personnel)	4	4	4	2	4	2	2	4	4	4	4	4	2	4	2	2	4	4
6	Assistance (Technical Personnel)	4	4	4	2	4	2	4	4	4	4	4	4	2	4	2	4	4	4
7	Assistance (Supervisor or Contractor Personnel)	4	4	2	2	4	2	2	4	4	4	4	2	2	4	2	2	4	4
	TOTAL	**28**	**28**	**24**	**14**	**28**	**20**	**24**	**26**	**26**	**26**	**26**	**24**	**14**	**28**	**20**	**24**	**26**	**26**
	Check List C: Maintenance Skills (Human Factors)	Uplock	Uplock Jack	Radius Rod	Main Gear Leg	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy	Uplock	Uplock Jack	Nose Leg Retraction Jack	Leg Cylinder	Anti Skid	Main Wheel	Brake System	Yoke Bearing	Toggle Assy
1	Arm, Leg, and Back Strength	4	4	4	3	4	3	3	4	4	4	4	4	3	4	3	3	4	4
2	Endurance and Energy	4	4	4	3	4	3	3	4	4	4	4	4	3	4	3	3	4	4
3	Eye-hand Coordination, Manual Dexterity and Ne	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
4	Visual Acuity	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
5	Logical Analysis	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
6	Memory - Things and Ideas	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
7	Planfulness and Resourcefulness	4	4	2	3	3	3	3	3	3	4	4	2	3	3	3	3	3	3
8	Alertness, Cautiousness and Accuracy	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
9	Concentration, Persistence and Patience	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
10	Initiative and Incisiveness	3	3	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
	TOTAL	**33**	**33**	**10**	**9**	**11**	**9**	**9**	**11**	**11**	**33**	**33**	**10**	**9**	**11**	**9**	**9**	**11**	**11**
	Corrective Maintenance Task Time (Mct) in MINUTES	37.74	37.74	70.78	109.84	36.82	76.31	57.59	53.41	53.41	48.77	43.44	100.15	123.31	36.82	76.31	57.59	53.41	53.41
	Corrective Maintenance Task Time (Mct) in HOURS	0.63	0.63	1.18	1.83	0.61	1.27	0.96	0.89	0.89	0.81	0.72	1.67	2.06	0.61	1.27	0.96	0.89	0.89
	TOTAL (HOURS)	**1.26**		**1.18**	**6.46**						**1.54**		**8.35**						

7.2.5 **Summary – Validation 2**

There are two scenarios of results from second validation. Table 7-20 shows the summary for both maintenance allocation time and maintainability prediction. Meanwhile Figure 7—17 illustrated the summary results. Collectively, the results indicate that the MTTR 1.00 hour shows the poor results compare MTTR 3.76 hours. By using MTTR 1.00 hour all components falls below maintenance allocation and all components need to re-examine for the maintainability prediction time. In MTTR 3.76 hours which is the value of average from the maintainability prediction time shows only two components need to consider for maintainability re examination.

Clearly, the value of MTTR = 1.00 hour is not suitable for this second validation process. As the MTTR value is change to 3.76 hours which is the average of maintainability prediction methodology, the results show some improvement. Therefore, the in this second validation process required large number of MTTR.

Table 7-20 The summary of maintainability allocation and prediction tasks time for Jetstream 31 both MTTR values

No	Components	Maintainability Prediction Time (Hour)	Maintainability Allocation Time (hour)		Decision	
			MTTR = 1.00	MTTR = 3.76	MTTR = 1.00	MTTR = 3.76
1	Main Gear Uplock Assembly	1.26	0.51	1.90	NOT GOOD	GOOD
2	Main Landing Gear Radius Rod	1.18	0.72	2.71	NOT GOOD	GOOD
3	Main Landing Gear	6.46	1.01	3.80	NOT GOOD	NOT GOOD
4	Nose Gear Uplock Assembly	1.54	0.51	1.90	NOT GOOD	GOOD
5	Nose Landing Gear	8.35	1.01	3.80	NOT GOOD	NOT GOOD
	Average	3.76				

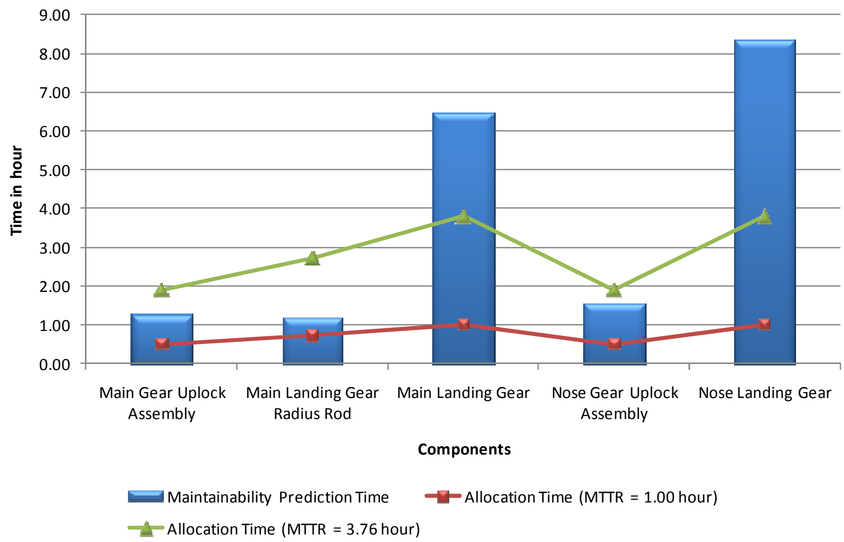


Figure 7—17 The trend of maintainability prediction and allocation times for both MTTR values for Jetstream 31 Landing Gear

Alternatively, to identify the most appropriate MTTR value for Jetstream 31 validation process, the author decided to apply Equation 4-4, Equation 4-5, and Equation 4-6 to calculate potential MTTR value. There are two main inputs in this process; namely 1) Availability and 2) Mean Time Between Failure (MTBF).

The MTBF value can be calculate based on Equation 4-4. For Availability value the author decided to used acceptable assumption which is 99.70% Availability or A = 0.997 as per advice by industry expert. The results of this process are shown Table 7-21 below. Meanwhile Figure 7—18 illustrate the summary of all results of Jetstream 31. This exercise successfully proves that the second validation process required more than 3.76 hours of MTTR by using above mentioned formulas.

Table 7-21 The Jetstream 31 validation process by using formula

No	Components	List of Modules	Allocation (Kj)			Σ Kj	λ	λj Kj	Allocated Rpj	λRpj
			Module	Isolation	Accessiblity		Fail/Cycles 106		(hour)	
1	Main Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.298851	16.09	7.20	16.55
2	Main Landing Gear Radius Rod	Electromechanical Equipment + Interconnection (Mechanical)	3	4	3	10	7.994200	79.94	10.28	82.21
3	Main Landing Gear	Mechanical Structure with mechanism	8	4	2	14	249.740504	3,496.37	14.40	3595.70
4	Nose Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.298851	16.09	7.20	16.55
5	Nose Landing Gear	Mechanical Structure with mechanism	8	4	2	14	177.916948	2,490.84	14.40	2561.61
								6,099.33		6,272.62

$\lambda_{\text{Landing Gear}}$	211.191121	Fail/Cycles 10^6
Availability (A)	0.997	
MTBF = 1/λ	4,735	hour
MTTR = [MTBF(1-A)]/A	14.25	hour
K = Σ λj Kj / Σ λ	13.85	
Rpj = (MTTR/K)*Kj	1.0284	
Check: $MTTR_{system}$ = Σ λRpj/Σ λ	14.25	hour
RESULT	GOOD	

Input Values

Calculated Values

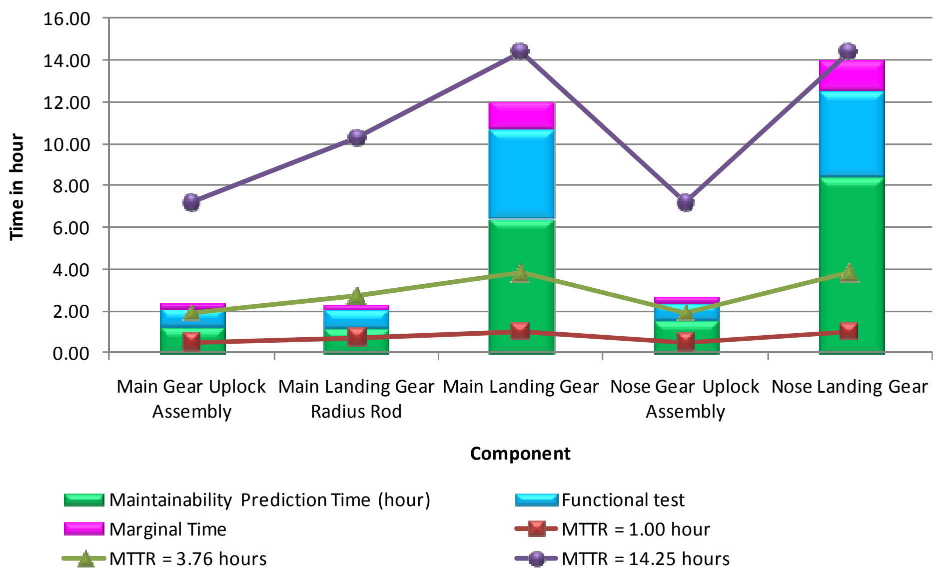


Figure 7—18 The summary of ALL results for Jetstream 31

7.3 Validation conclusion

The developed methodology has been tested and validated by using approved industrial references. The information has been provided and confirmed by aircraft certified personnel. The author also used and analysed the data information from reliable sources of information. The predicted task times are not only restricted to the most suitable maintenance task times but also include the appropriate approach and methodology to perform the maintainability prediction. Both aircraft have shown indications of successful results. Both aircraft types have been tested by using improved maintainability allocation and the final results shown the same trends as the data supplied by industry as well as estimation MTTR.

The maintenance task time has been predicted by existing maintainability prediction known as MIL-HDBK-472, procedure III. The existing maintainability prediction methodology has been improved by the author through the development of a new quantitative approach in checklist C. The improved quantitative approach has been tested and validated by using two types of aircraft (i.e. BAe 146 and Jetstream).

Based on two validation processes the elements of human capabilities and number of maintenance sequential have been used in determining the most suitable score value for checklist C for each component in order to calculate the potential maintenance task time. The results are considerably accurate because the score value is assigned based on physical aircraft components. If the size of components is small and less than 5 lbs weight therefore the maintenance task required less effort remove and replace the affected components.

Overall, feedback information contributes data for future reliability and repair time predictions. The SDR analysis does indicate some deficiencies in design activities and service difficulty trend. Secondly, the maintenance allocation methodology does provide the maximum task time for each individual components. Thirdly, the improved check list C in MIL-HDBK-472, procedure III ease to identify the most appropriate score value than before where most of the times the estimation element is used to assign the score value. At the same time allow routine maintenance to be revised.

8 Discussion

8.1 Service Difficulties Report (SDR)

The availability of feedback information in aviation industry has been investigated. Based on the collection of sources of feedback information, it is of utmost importance to know the **purpose of feedback information** because it is valuable information that is capable of assisting future design improvements and enhancements. It is clear that different types of industry deal with the question of the role and purpose of feedback information from different perspectives. However, there are some common features:

1. The collection of historical information is to aid in decision making for further enhancement.
2. The information which indicates the condition, performance and/or trend of specific products/systems.
3. The indication of the success of the developed products/systems.
4. Collective information which can be used to identify, propose and improve the performance of developed products/systems.
5. Collective information used to determine, propose and improve any potential error corrective and detection for future products/systems development.
6. Collective information to set a level of confidence for the rejection and acceptance regions of developed products/systems.

The values of a feedback system can be accessed through appropriately evaluating the feedback information by using suitable existing tools. One difficulty that has been identified from this investigation of information sources is that the information collected may be contained in large, complex datasets from which it is time consuming for the designer to extract the required information. Service Difficulty Reporting System (SDRS), due to its availability, accessibility, and data information arrangement (i.e.: JASC Code, Part Condition, Part Name) is good potential feedback information source for a design improvement as well as maintainability prediction improvement.

A detailed analysis of the SDR data has been performed to demonstrate how the data could be used to provide feedback information for maintainability prediction. A global evaluation of the SDR data has provided general trends for different component types on aircraft. A more detailed analysis at the component level provides information of greater direct relevance to the designer in understanding the potential causes of in-service failures.

For example, the analysis of aircraft doors has highlighted that the frequent opening of the doors causes potential failures such as dents, being unsecured and other types of discrepancy. Once this has happened, such components need to be repaired or replaced within the specified time with available resources such as manpower and tools. The feedback about the frequencies of such incidents provides an indication to the designer of the potential problem associated with door access and opening/closing, so that better prediction and/or improvement in the design can be proposed. To date such feedback information has not been readily available to the designer.

In this research, the author made an attempt to use the Equation 3-1 to convert the analysed SDR into service difficulties rate. This is performed to identify any potential correlation between service difficulties and failure rate. As a result there is no correlation between service difficulties rate and failure rate which previously described in section 3.6.

Overall, the results of the SDRS studies have not led to significant surprises. However, the quantification of the magnitude of problems may be used to focus on design solutions. Furthermore, based on an extensive study of sources of feedback information, the author has concluded that existing feedback information can be summarised into three categories:

1. Collective type (i.e. Maintenance Error Decision Aid (MEDA), Service Difficulty Reporting Systems (SDRS), Government-Industry Data Exchange Program (GIDEP), and Air Accident Investigation Branch reports (AAIB));
2. Regulatory type (i.e. Airworthiness Directive (AD) and Service Bulletin (SB));
3. Monitoring type (i.e. Aircraft Engine Health/Monitoring Systems, Aircraft Tyre Monitoring Systems, Aircraft Systems Monitoring Systems (Hydraulic Pump), Structural Health Monitoring Systems (SHMS), and Integrated Vehicle/Structural Health Monitoring (IVHM/ISHM)).

A detailed analysis of Service Difficulty Reporting data has demonstrated that it is possible to use SDR data to support the maintainability prediction activities by providing trends of the frequency and causes of service difficulties, classified by aircraft component. This information will be of benefit to aircraft designers in understanding the causes of maintenance related problems for in-service aircraft.

There is no doubt that feedback information is able to contribute an important role in the design activities. The design stage is the best option for the designer to design and develop systems in order to reduce the service difficulties from a maintainability perspective.

Others types of information also should be considered from lower level events including confidential reporting systems, Flight Data Monitoring, and others which could be used for further investigation as well as valuable information.

8.2 Maintainability allocation methodology

The existing maintainability allocation methodology has been improved by the author. The improved methodology is performed by adding more modules and score values related to mechanical aircraft components (i.e. Landing Gear, Mechanical parts). The additional modules and score values have been tested and validated by using several case studies (i.e. Fuel System and Communication Systems).

The additional modules have been assigned with specific score values. The improved methodology, testing and validation results have been described in section 4.3. The linear formula, as shown below, has been chosen as the primary formula to calculate the new score values for new modules and shown in Table 4-6.

$$y = 1.4364x + 1.769 \quad \textbf{Equation 8-1}$$

Furthermore, to ensure the developed methodology and improved approach is applicable to industry, the two approved aircraft have been used for further testing and validation processes. The case studies have been tested and validated in accordance with the approved maintenance manual supplied by a certified aircraft Maintenance and Repair Organisation (MRO). Overall, the results are very successful.

8.3 Maintainability prediction methodology

This section present the works that have been performed with the intention of using the element of improved maintainability allocation, as previously described. This also includes identifying the element of value added into the existing maintainability prediction methodology, specifically procedure III. The initial outcome from this effort shows an element of success, as previously described in chapter 5. The outcome also shows that there is potential to utilise human data as one of the sources of information to improve the existing prediction method. This is performed through the improved approach carried out by the author in MIL-HDBK-472, procedure III, in checklist C. Checklist C is the section which asked questions related to human capabilities. Although this piece of work shows only a very fundamental effort, at least it offers and generates ideas for future research development.

The case studies have been used to ensure the developed approach is applicable. The author used both BAe 146 – 300 and Jetstream 31 for the case study due to availability and courtesy from the certified MRO. The list of components and historical data were extracted from reliable sources, i.e. from the approved MRO, and compared with the Service Difficulty Reporting System (SDRS) accessible data [118]. In addition, the Civil Aircraft Airworthiness Information and Procedures (CAAIP) [107] were used as a general guide to identify potential score values for each question under each MIL-HDBK-472, Procedure III checklist.

Before performing the maintainability prediction, the author applied the improved maintainability allocation method as one of the procedures in maintainability prediction methodology. The purpose was to have a task time target for each component. Through this approach, the author believes that the designer has a greater role in effectively designing components. Table 7-5, Table 7-9, Table 7-10, and Table 7-17 show the list of components and the maintainability allocation results. The maintainability allocation was performed by using improved modules and score values.

In the initial stage of maintainability prediction, the author prepared a generic list of landing gear components. The purpose of performing initial stage of maintainability prediction was to ensure the author had a better understanding of MIL-HDBK-472, procedure III, and to identify the strengths and weaknesses of this approach for the purpose of further improvement.

The maintainability prediction in checklists A (Design) and B (Facilities) were evaluated based on observations made at the approved MRO and advice from industrial experts. In addition, the general guideline from Civil Aircraft Airworthiness Information and Procedures (CAAIP) was also used [107].

9 Conclusion and Future research

9.1 Conclusion

Application of the techniques contained in this research will help to promote consistency in the development of aviation forecasts. The most important conclusions drawn from this research are:

1. A method has been developed to allow historical data of feedback information to help aircraft designer to understand the trends of service difficulties and failure in in-service aircraft;

2. An improved maintainability allocation has been developed that can be used in the early stages of the design process to provide a maximum allowable task time;

3. The developed approach for maintainability prediction offers the opportunity to accurately predict the maintainability related to human factors, hence reducing the potential human errors because the approach is developed in accordance with human data and capabilities;

4. The developed methodology could be more useful if actual data is available for the purpose of validation. At the same time, the element of potential financial benefits such as the element of reduction maintenance cost flight hour. Furthermore, the benefits of utilising the developed methodology in this research will be able to reduce human related errors as well as design errors, improved maintenance schedule process, improved maintenance activities, and increase customers satisfactions. This is because the SDRS contains information such as JASC Code which the design will be able to focus on specific JASC for future improvement. Other than that SDRS contains information such as Stage of Operation where the specific maintenance difficulties are discovered, Type of Aircrafts as well as aircraft model which have contributed the most maintenance difficulties. Based on this information which also considered as feedback information, the future aircraft design can be improved and consequently contributed to improvement of aircraft maintenance activities.

9.2 Research Contribution

The contribution of this thesis can be stated as follows:

1. Contribution to the Prediction Methodology.
2. Contribution to Academic Theory.

9.2.1 **Contribution to the maintainability prediction methodology**

The main intention of this research has been to look for alternative solutions to predict the maintainability prediction from the perspective of academicians. In particular, this research argues that existing approaches for predicting maintainability at the conceptual design phase have only been focusing on the failure rate (λ) and that many other maintenance problems were very seldom taken into consideration during prediction. Failure can be from primary and/or secondary causes. This research made an effort to explore the information within the secondary failure such as manufacturing causes and other related elements.

This research therefore contributes to the existing body of knowledge by offering an alternative maintainability prediction method that is based on valuable information from the end user which can be used during the early aircraft conceptual design stage. Overall, this piece of research work has contributed some values and to knowledge as follows:

1. Based on advices and opinions from aircraft maintenance practitioners/experts the predicted values were acceptable because they are below real industrial task times;
2. The idea proposed in this research is a starting point for further investigation and better maintainability prediction through the integration of human data into design consideration.
3. This research has proved that the elements of human factors, human error and human data are able to improve maintainability prediction and therefore the author encourages the future development of maintainability prediction to include and consider the above mentioned elements.

9.2.2 **Contribution to academic theory**

This research contributes to the opportunities for academicians to use alternative inputs to propose, improve and predict future potential aircraft design.

However, these inputs have to be finalised or compared to real in-service feedback information which is collected by major aircraft manufacturers (i.e. Boeing and Airbus). In addition, the research is able to offer others potential techniques to be developed to accurately use and quantitatively convert the information from the user into some form of quantitative element such as rate. In this research all analysed feedback information was converted into service difficulty rate, abbreviated to SR. The analysed feedback information does show significant information for future improvement. The quantitative prediction can never be complete, and therefore this research offers many more opportunities to utilise aircraft related feedback information for potentially long-term design improvement.

9.3 Suggestions & Potential for Future Research/Work

This research attempt to extract and show the important as well as valuable information contains within feedback information. The selected feedback information in this research (i.e.: SDRS) be able to offer numerous causes & affect of existing discrepancies. At the same time when and how the discrepancies happened also mentioned within the feedback information. The author is able to analyse all of these information effectively. However, the analyses could be more accurate if there are cooperation and support from industry by providing real data information.

Based on the research conclusions and finding issues, the author proposes the following suggestions for future and potential research:

1. Improve the development of a systematic methodology to gather data from in-service aircraft information before being channelled to the design team;
    a. To design appropriate/suitable methodology to convert as well as summarise the whole set of feedback information into valuable information to be use for future design improvement.
2. Develop the overall maintainability assessment is to be performed on particular and/or all aircraft systems using real in-service maintenance difficulties reported. The process could be as follows:
    a. To collect real maintenance task time by using stop watch to and further to compare the collected real maintenance time to the predicted maintenance time;
3. Identify the importance measures for aircraft maintenance related feedback formation and compare to Failure Rate (λ).

a. Analysed information has to be converted into quantitative information such as total operations time (i.e.: Total engine run in hour, Total flying hours).

The benefits of those main element of future works as previously mentioned is not only limited to identify the most effective method to predict the maintainability effective but it is also to identify the potential cost benefits. The actual data supply by industry is one of the suitable and effective ways to make this research successful as well as could be a better approach for future aircraft design and development.

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APPENDICES

Appendix A Regulation Issues: EASA Part 145

In aircraft maintenance, all personal involved in aircraft maintenance activities are required to record all work carried out. This is clearly stated in Official Journal of European Journal, 2003a & b.

145. A.45 Maintenance data

a) *The organisation shall hold and use applicable current maintenance data in the performance of maintenance, including modifications and repairs. 'Applicable' means relevant to any aircraft, component or process specified in the organisation's approval class rating schedule and in any associated capability list.*

b) *For the purposes of this Part, applicable maintenance data shall be any of the following:*

   4. *Any applicable standard, such as but not limited to,* ***maintenance standard practices*** *recognised by the Agency as a good standard for maintenance;*

d) *The organisation may only modify maintenance instructions in accordance with a procedure specified in the maintenance organisation's exposition. With respect to those changes, the organisation shall demonstrate that they result in* ***equivalent or improved*** *maintenance standards and shall inform the type-certificate holder of such changes. Maintenance instructions for the purposes of this paragraph means instructions on* ***how to carry out the particular maintenance task: they exclude the engineering design of repairs and modifications.***

f) *The organisation shall ensure that all applicable maintenance data is readily available for use when required by maintenance personnel.*

g) *The organisation shall establish a procedure to* ***ensure that maintenance data it controls is kept up to date.*** *In the case of operator/customer controlled and provided maintenance data, the organisation shall be able* ***to show that either it has written confirmation from the operator/customer that all such maintenance data is up to date*** *or it has work orders specifying the amendment status of the maintenance data to be used or it can show that it is on the operator/customer maintenance data amendment list.*

145. A.55 Maintenance records

a) *The organisation shall* ***record all*** *details of maintenance work carried out. As a minimum, the organisation shall retain records necessary to prove that all* *requirements have been met for issuance of the certificate of release to service, including subcontractor's release documents.*

b) *The organisation shall provide a copy of each certificate of release to service to the aircraft operator, together with a copy of any specific approved repair/modification data used for repairs/modifications carried out.*

c) *The organisation shall retain a copy of all detailed maintenance records and any associated maintenance data for two years from the date the aircraft or component to which the work relates was released from the organisation.*

1. *Records under this paragraph* ***shall be stored in a safe way*** *with regard to fire, flood and theft.*
2. *Computer backup discs, tapes etc. shall be stored in a different location from that containing the working discs, tapes etc., in an environment that ensures they remain in good condition.*
3. *Where an organisation approved under this Part terminates its operation, all retained maintenance records covering the last* ***two years*** *shall be distributed to the last owner or customer of the respective aircraft or component or* ***shall be stored*** *as specified by the competent authority.*

145. A.60 Occurrence reporting

a) *The organisation shall report to the competent authority, the state of registry and* ***the organisation responsible for the design of the aircraft or component*** *any condition of the aircraft or component identified by the organisation that has resulted or may result in an unsafe condition that hazards seriously the flight safety.*

b) *The organisation shall establish an internal occurrence reporting system as detailed in the exposition to enable the collection and evaluation of such reports, including the assessment and extraction of those occurrences to be reported under paragraph (a).* ***This procedure shall identify adverse trends, corrective actions taken or to be taken by the organisation to address deficiencies and include evaluation of all known relevant information relating to such occurrences and a method to circulate the information as necessary.***

c) *The organisation shall make such reports in a form and manner established by the Agency and ensures that they contain all pertinent information about the condition and evaluation results known to the organisation.*

d) ***Where the organisation is contracted by a commercial operator to carry out maintenance, the organisation shall also report to the operator any such condition affecting the operator's aircraft or component.***

e) The organisation shall produce and submit such reports as soon as practicable but in any case within 72 hours of the organisation identifying the condition to which the report relates.

145. A.65 Safety and quality policy, maintenance procedures and quality system

*4. Maintenance procedures shall be established to ensure that damage is assessed and **modifications and repairs are carried out using data approved by the Agency or by an approved Part-21 design organisation, as appropriate.***

*c) **The organisation shall establish** a quality system that includes the following:*

*1) Independent audits in order **to monitor compliance** with required aircraft/aircraft component standards and adequacy of the procedures to ensure that such procedures invoke good maintenance practices and airworthy aircraft/aircraft components. In the smallest organisations the independent audit part of the quality system may be contracted to another organisation approved under this Part or a person with appropriate technical knowledge and proven satisfactory audit experience; and*

*2) **A quality feedback reporting system** to the person or group of persons specified in 145.A.30 (b) and ultimately to the accountable manager that ensures proper and timely corrective action is taken in response to reports resulting from the independent audits established to meet paragraph (1).*

Appendix B Service Difficulties Report global analyses

Table B-1 Service Difficulties Report (SDR) analyses in accordance with four main categories

SYSTEM	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%	AVERAGE
AIRCRAFT	7	13	161	199	305	77	36	78	61	62	999	0.24%	100
AIRFRAME SYSTEMS	40,555	37,326	32,435	31,204	33,640	34,681	43,454	46,917	47,194	49,406	396,812	93.40%	39,681
PROPELLER/ROTOR SYSTEMS	291	392	1,062	1,555	502	315	225	209	186	136	4,873	1.15%	487
POWERPLANT SYSTEM	2,238	2,386	2,937	2,735	2,176	1,985	1,998	1,956	1,879	1,860	22,150	5.21%	2,215
											424,834	100.00%	

Table B-2 SDR analyses in accordance with Airframe systems

AIRRAME SYSTEMS	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%	AVERAGE
2XXX	5,171	6,275	6,238	6,397	5,943	5,943	7,492	7,152	6,856	6,237	63,704	16.14%	6,370
3XXX	8,693	8,911	7,994	8,114	7,518	7,186	9,667	12,037	12,161	13,098	95,379	24.16%	9,538
4XXX	175	198	208	170	192	209	258	351	320	410	2,491	0.63%	249
5XXX	26,352	21,716	17,807	16,350	19,827	21,192	25,848	27,154	27,649	29,333	233,228	59.07%	23,323
											394,802	100.00%	

Table B-3 SDR analyses in accordance with 2 series JASC Code of Airframe systems

AIRRAME SYSTEMS (2XXX)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%	AVERAGE
21 AIR CONDITIONING	933	953	851	756	824	950	1,135	1,232	1,219	1,177	10,030	15.74%	1,003
22 AUTO FLIGHT	83	284	225	302	268	148	259	140	123	114	1,946	3.05%	195
23 COMMUNICATIONS	87	88	175	254	106	107	140	148	145	180	1,430	2.24%	143
24 ELECTRICAL POWER	433	510	628	702	408	392	460	507	533	513	5,086	7.98%	509
25 EQUIPMENT/FURNISHINGS	1,065	1,178	1,185	1,342	1,497	1,195	1,389	1,954	1,952	1,910	14,667	23.02%	1,467
26 FIRE PROTECTION	651	766	720	813	651	528	599	785	790	482	6,785	10.65%	679
27 FLIGHT CONTROLS	1,199	1,721	1,451	1,281	1,484	1,954	2,757	1,561	1,307	1,048	15,763	24.74%	1,576
28 FUEL	195	204	364	401	238	174	246	257	269	337	2,685	4.21%	269
29 HYDRAULIC POWER	525	571	639	546	467	495	507	568	518	476	5,312	8.34%	531
											63,704	100.00%	

Table B-4 SDR analyses in accordance with 3 series JASC Code of Airframe systems

AIRRAME SYSTEMS (3XXX)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%	AVERAGE
30 ICE AND RAIN PROTECTION	272	311	271	230	243	213	235	332	248	228	2,583	2.65%	258
31 INSTRUMENTS	139	189	255	206	149	150	497	414	277	235	2,511	2.58%	251
32 LANDING GEAR	2,030	1,790	1,928	1,945	1,722	1,819	1,698	2,068	1,880	1,691	18,571	19.07%	1,857
33 LIGHTS	5,612	5,869	4,739	4,758	4,702	4,416	6,493	8,510	8,988	10,270	64,357	66.08%	6,436
34 NAVIGATIONS	547	641	753	909	634	504	646	456	444	515	6,049	6.21%	605
35 OXYGEN	72	85	30	44	45	61	77	226	291	122	1,053	1.08%	105
36 PNEUMATIC	164	226	188	173	160	151	189	223	208	328	2,010	2.06%	201
37 VACUUM	4	7	3	9	6	4	3	3	3	4	46	0.05%	5
38 WATER/WASTE	17	19	15	13	17	19	18	28	30	33	209	0.21%	21
											97,389	100.00%	

Table B-5 SDR analyses in accordance with 5 series JASC Code of Airframe systems

AIRRAME SYSTEMS (5XXX)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL	%	AVERAGE
51 STANDARDS PRACTICES/STRUCTURES	6	70	18	17	23	97	647	142	100	25	1,145	0.49%	115
52 DOORS	1,873	1,472	1,365	1,277	1,319	1,548	1,771	2,268	2,272	2,575	17,740	7.61%	1,774
53 FUSELAGE	19,719	16,190	13,049	10,765	13,047	14,831	17,629	19,033	19,397	21,010	164,670	70.60%	16,467
54 NACELLES/PYLONS	332	364	469	514	353	359	588	597	632	428	4,636	1.99%	464
55 STABILIZERS	964	769	683	817	1,110	1,112	1,015	1,136	1,107	815	9,528	4.09%	953
56 WINDOWS	223	342	294	239	231	246	312	319	266	244	2,716	1.16%	272
57 WINGS	3,235	2,509	1,929	2,721	3,744	2,999	3,886	3,659	3,875	4,236	32,793	14.06%	3,279
											233,228	**100.00%**	

Appendix C Aircraft Hours Flown

Table C-1 The information for aircraft hours flown [153]

Year	Aircraft Hours Flown (Millions)	
	Air Carrier	General Aviation
1990	12.150	28.510
1991	11.781	27.678
1992	12.360	24.780
1993	12.706	22.796
1994	13.124	22.235
1995	13.505	24.906
1996	13.746	24.881
1997	15.838	25.591
1998	16.817	25.518
1999	17.555	29.246
2000	18.299	27.838
2001	17.814	25.431
2002	17.290	25.545
2003	17.468	25.998
2004	18.883	24.888
2005	19.390	23.168
2006	19.263	23.963
2007	19.637	23.819
2008	19.098	22.805
2009	18.001	20.456

Appendix D Case study 1 – Aircraft fuel systems

Table D-1 Service difficulties rate for Aircraft fuel systems

No	System / Sub System		CODE	FEEDBACK	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	AVERAGE
					18.299	17.814	17.290	17.468	18.883	19.390	19.263	19.637	19.098	18.001	
1	Hand Pump	Pump	977	292	1.5957E-05	1.6392E-05	1.6888E-05	1.6716E-05	1.5464E-05	1.5059E-05	1.5159E-05	1.4870E-05	1.5290E-05	1.6221E-05	1.5802E-05
2	Reservoir Fill Selection Valve (RFSV)	Selector Valve	1113	10	5.4648E-07	5.6136E-07	5.7837E-07	5.7248E-07	5.2958E-07	5.1573E-07	5.1913E-07	5.0924E-07	5.2362E-07	5.5552E-07	5.4115E-07
3	Pressure Valve (PV)	Pressure Valve	955	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
4	Reservoir	Reservoir	1013	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
5	Non Return Valve (NRV)	Valve	1427	166	9.0715E-06	9.3185E-06	9.6009E-06	9.5031E-06	8.7910E-06	8.5611E-06	8.6176E-06	8.4534E-06	8.6920E-06	9.2217E-06	8.9831E-06
6	Engine Driven Pump (EDP)	Pump	977	292	1.5957E-05	1.6392E-05	1.6888E-05	1.6716E-05	1.5464E-05	1.5059E-05	1.5159E-05	1.4870E-05	1.5290E-05	1.6221E-05	1.5802E-05
7	Non Return Valve (NRV)	Valve	1427	166	9.0715E-06	9.3185E-06	9.6009E-06	9.5031E-06	8.7910E-06	8.5611E-06	8.6176E-06	8.4534E-06	8.6920E-06	9.2217E-06	8.9831E-06
8	Aircraft Motor Pump (ACMP)	Pump	977	292	1.5957E-05	1.6392E-05	1.6888E-05	1.6716E-05	1.5464E-05	1.5059E-05	1.5159E-05	1.4870E-05	1.5290E-05	1.6221E-05	1.5802E-05
9	Non Return Valve (NRV)	Valve	1427	166	9.0715E-06	9.3185E-06	9.6009E-06	9.5031E-06	8.7910E-06	8.5611E-06	8.6176E-06	8.4534E-06	8.6920E-06	9.2217E-06	8.9831E-06
10	Pipe	Pipe	904	5	2.7324E-07	2.8068E-07	2.8918E-07	2.8624E-07	2.6479E-07	2.5786E-07	2.5956E-07	2.5462E-07	2.6181E-07	2.7776E-07	2.7057E-07
11	Pump Overheat Light (POL 1)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
12	Pump Overheat Light (POL 2)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
13	Pump Low Light (PLL 1)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
14	Pump Low Light (PLL 2)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
15	Heat Exchanger (HEX)	Heat Exchanger	644	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
16	Hydraulic Low Light (HLL 1)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
17	Hydraulic Low Light (HLL 2)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
18	Hydraulic Low Light (HLL 3)	Light	759	1	5.4648E-08	5.6136E-08	5.7837E-08	5.7248E-08	5.2958E-08	5.1573E-08	5.1913E-08	5.0924E-08	5.2362E-08	5.5552E-08	5.4115E-08
19	Hydraulic Quantity Indicator (HQ 1)	Indicator	691	113	6.1752E-06	6.3433E-06	6.5356E-06	6.4690E-06	5.9842E-06	5.8277E-06	5.8662E-06	5.7544E-06	5.9168E-06	6.2774E-06	6.1150E-06
20	Hose	Hose	662	21	1.1476E-06	1.1788E-06	1.2146E-06	1.2022E-06	1.1121E-06	1.0830E-06	1.0902E-06	1.0694E-06	1.0996E-06	1.1666E-06	1.1364E-06
21	Depressurisation Valve (DPV)	Valve	1427	166	9.0715E-06	9.3185E-06	9.6009E-06	9.5031E-06	8.7910E-06	8.5611E-06	8.6176E-06	8.4534E-06	8.6920E-06	9.2217E-06	8.9831E-06
22	Non Return Valve (NRV)	Valve	1427	166	9.0715E-06	9.3185E-06	9.6009E-06	9.5031E-06	8.7910E-06	8.5611E-06	8.6176E-06	8.4534E-06	8.6920E-06	9.2217E-06	8.9831E-06
23	Moisture Vent Trap (MVT)	Vent	1438	9	4.9183E-07	5.0522E-07	5.2053E-07	5.1523E-07	4.7662E-07	4.6416E-07	4.6722E-07	4.5832E-07	4.7125E-07	4.9997E-07	4.8703E-07

Number of flight flown hours per year (millions)

Average difficulties rate

Appendix E Case Study 2 – Aircraft Communications

Table E-1 Service difficulties rate for Aircraft Communication

NO	SUB SYSTEM		CODE	FEEDBACK	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	AVERAGE
					18.299	17.814	17.29	17.468	18.883	19.39	19.263	19.637	19.098	18.001	
1	Audio Selector Panel 1	Audio Panel	68	35	1.91267E-06	1.96475E-06	2.02429E-06	2.00366E-06	1.85352E-06	1.80505E-06	1.81695E-06	1.78235E-06	1.83265E-06	1.94434E-06	1.89402E-06
2	Audio Selector Panel 2	Audio Panel	68	35	1.91267E-06	1.96475E-06	2.02429E-06	2.00366E-06	1.85352E-06	1.80505E-06	1.81695E-06	1.78235E-06	1.83265E-06	1.94434E-06	1.89402E-06
3	Headset 1	Headset	642	13	7.10421E-07	7.29763E-07	7.5188E-07	7.44218E-07	6.8845E-07	6.70449E-07	6.74869E-07	6.62016E-07	6.807E-07	7.22182E-07	7.03495E-07
4	Headset 2	Headset	642	13	7.10421E-07	7.29763E-07	7.5188E-07	7.44218E-07	6.8845E-07	6.70449E-07	6.74869E-07	6.62016E-07	6.807E-07	7.22182E-07	7.03495E-07
5	Handheld Microphone 1	Microphone	819	33	1.80338E-06	1.85248E-06	1.90862E-06	1.88917E-06	1.7476E-06	1.70191E-06	1.71313E-06	1.6805E-06	1.72793E-06	1.83323E-06	1.78579E-06
6	Handheld Microphone 2	Microphone	819	33	1.80338E-06	1.85248E-06	1.90862E-06	1.88917E-06	1.7476E-06	1.70191E-06	1.71313E-06	1.6805E-06	1.72793E-06	1.83323E-06	1.78579E-06
7	Speaker 1	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
8	Speaker 2	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
9	VHF 1 Antenna	Antenna	50	46	2.5138E-06	2.58224E-06	2.6605E-06	2.63339E-06	2.43605E-06	2.37236E-06	2.388E-06	2.34252E-06	2.40863E-06	2.55541E-06	2.48929E-06
10	VHF 1 Transceiver	Transceiver	1369	217	1.18586E-05	1.21814E-05	1.25506E-05	1.24227E-05	1.14918E-05	1.11913E-05	1.12651E-05	1.10506E-05	1.13624E-05	1.20549E-05	1.17429E-05
11	VHF 1 Control Panel	Control Panel	292	56	3.06028E-06	3.14359E-06	3.23887E-06	3.20586E-06	2.96563E-06	2.88809E-06	2.90713E-06	2.85176E-06	2.93224E-06	3.11094E-06	3.03044E-06
12	VHF 2 Antenna	Antenna	50	46	2.5138E-06	2.58224E-06	2.6605E-06	2.63339E-06	2.43605E-06	2.37236E-06	2.388E-06	2.34252E-06	2.40863E-06	2.55541E-06	2.48929E-06
13	VHF 2 Transceiver	Transceiver	1369	217	1.18586E-05	1.21814E-05	1.25506E-05	1.24227E-05	1.14918E-05	1.11913E-05	1.12651E-05	1.10506E-05	1.13624E-05	1.20549E-05	1.17429E-05
14	VHF 2 Control Panel	Control Panel	292	56	3.06028E-06	3.14359E-06	3.23887E-06	3.20586E-06	2.96563E-06	2.88809E-06	2.90713E-06	2.85176E-06	2.93224E-06	3.11094E-06	3.03044E-06
15	HF Antenna	Antenna	50	46	2.5138E-06	2.58224E-06	2.6605E-06	2.63339E-06	2.43605E-06	2.37236E-06	2.388E-06	2.34252E-06	2.40863E-06	2.55541E-06	2.48929E-06
16	HF Lightning Arrestor	Light	759	1	5.46478E-08	5.61356E-08	5.78369E-08	5.72475E-08	5.29577E-08	5.1573E-08	5.1913E-08	5.09243E-08	5.23615E-08	5.55525E-08	5.4115E-08
17	HF Antenna Coupler	Coupler	314	58	3.16957E-06	3.25587E-06	3.35454E-06	3.32036E-06	3.07155E-06	2.99123E-06	3.01095E-06	2.95361E-06	3.03697E-06	3.22204E-06	3.13867E-06
18	HF Transceiver	Transceiver	1369	217	1.18586E-05	1.21814E-05	1.25506E-05	1.24227E-05	1.14918E-05	1.11913E-05	1.12651E-05	1.10506E-05	1.13624E-05	1.20549E-05	1.17429E-05
19	HF Control Panel	Control Panel	292	56	3.06028E-06	3.14359E-06	3.23887E-06	3.20586E-06	2.96563E-06	2.88809E-06	2.90713E-06	2.85176E-06	2.93224E-06	3.11094E-06	3.03044E-06
20	Selcal Decoder	Decoder	363	6	3.27887E-07	3.36814E-07	3.47021E-07	3.43485E-07	3.17746E-07	3.09438E-07	3.11478E-07	3.05546E-07	3.14169E-07	3.33315E-07	3.2469E-07
21	Selcal Control Panel	Control Panel	292	56	3.06028E-06	3.14359E-06	3.23887E-06	3.20586E-06	2.96563E-06	2.88809E-06	2.90713E-06	2.85176E-06	2.93224E-06	3.11094E-06	3.03044E-06
22	Passenger Address Amplifier 1	Amplifier	38	26	1.42084E-06	1.45953E-06	1.50376E-06	1.48844E-06	1.3769E-06	1.3409E-06	1.34974E-06	1.32403E-06	1.3614E-06	1.44436E-06	1.40699E-06
23	Passenger Address Amplifier 2	Amplifier	38	26	1.42084E-06	1.45953E-06	1.50376E-06	1.48844E-06	1.3769E-06	1.3409E-06	1.34974E-06	1.32403E-06	1.3614E-06	1.44436E-06	1.40699E-06
24	PA Speaker	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
25	PA Speaker	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
26	PA Speaker	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
27	PA Speaker	Speaker	1196	11	6.01126E-07	6.17492E-07	6.36206E-07	6.29723E-07	5.82535E-07	5.67303E-07	5.71043E-07	5.60167E-07	5.75977E-07	6.11077E-07	5.95265E-07
28	Cockpit Voice Recorder Control Panel	Recorder	999	1	5.46478E-08	5.61356E-08	5.78369E-08	5.72475E-08	5.29577E-08	5.1573E-08	5.1913E-08	5.09243E-08	5.23615E-08	5.55525E-08	5.4115E-08
29	Cockpit Voice Recorder	Recorder	999	1	5.46478E-08	5.61356E-08	5.78369E-08	5.72475E-08	5.29577E-08	5.1573E-08	5.1913E-08	5.09243E-08	5.23615E-08	5.55525E-08	5.4115E-08

Number of flight flown hours per year (millions)

Average difficulties rate

Appendix F Case study 3 – Landing Gear

Table F-1 Service difficulties rate for Aircraft Landing Gear

No	System / Sub System		CODE	FEEDBACK	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	AVERAGE
					18.299	17.814	17.290	17.468	18.883	19.390	19.263	19.637	19.098	18.001	
1	ACTUATOR		16	917	5.0112E-05	5.14764E-05	5.30364E-05	5.2496E-05	4.85622E-05	4.72924E-05	4.76042E-05	4.66976E-05	4.80155E-05	5.09416E-05	4.9623E-05
2	BRAKE		148	484	2.645E-05	2.71696E-05	2.79931E-05	2.77078E-05	2.56315E-05	2.49613E-05	2.51259E-05	2.46473E-05	2.5343E-05	2.68874E-05	2.6192E-05
3	BRAKE ASSY		149	417	2.2788E-05	2.34086E-05	2.4118E-05	2.38722E-05	2.20834E-05	2.15059E-05	2.16477E-05	2.12354E-05	2.18347E-05	2.31654E-05	2.2566E-05
4	CONNECTOR		275	395	2.1586E-05	2.21736E-05	2.28456E-05	2.26128E-05	2.09183E-05	2.03713E-05	2.05056E-05	2.01151E-05	2.06828E-05	2.19432E-05	2.1375E-05
5	CONTROL UNIT		300	302	1.6504E-05	1.6953E-05	1.74667E-05	1.72888E-05	1.59932E-05	1.5575E-05	1.56777E-05	1.53791E-05	1.58132E-05	1.67768E-05	1.6343E-05
6	LANDING GEAR		742	784	4.2844E-05	4.40103E-05	4.53441E-05	4.48821E-05	4.15188E-05	4.04332E-05	4.06998E-05	3.99246E-05	4.10514E-05	4.35531E-05	4.2426E-05
7	PROXIMITY SENSOR		968	529	2.8909E-05	2.96957E-05	3.05957E-05	3.02839E-05	2.80146E-05	2.72821E-05	2.7462E-05	2.69389E-05	2.76992E-05	2.93873E-05	2.8627E-05
8	PROXIMITY SWITCH		969	476	2.6012E-05	2.67206E-05	2.75304E-05	2.72498E-05	2.52079E-05	2.45487E-05	2.47106E-05	2.424E-05	2.49241E-05	2.6443E-05	2.5759E-05
9	SELECTOR VALVE		1113	439	2.399E-05	2.46435E-05	2.53904E-05	2.51317E-05	2.32484E-05	2.26405E-05	2.27898E-05	2.23558E-05	2.29867E-05	2.43875E-05	2.3756E-05
10	SENSOR		1116	390	2.1313E-05	2.18929E-05	2.25564E-05	2.23265E-05	2.06535E-05	2.01135E-05	2.02461E-05	1.98605E-05	2.0421E-05	2.16655E-05	2.1105E-05
11	STRUT		1270	540	2.951E-05	3.03132E-05	3.12319E-05	3.09137E-05	2.85972E-05	2.78494E-05	2.8033E-05	2.74991E-05	2.82752E-05	2.99983E-05	2.9222E-05
12	SWITCH		1286	575	3.1422E-05	3.2278E-05	3.32562E-05	3.29173E-05	3.04507E-05	2.96545E-05	2.985E-05	2.92815E-05	3.01079E-05	3.19427E-05	3.1116E-05
13	TIRE		1350	643	3.5139E-05	3.60952E-05	3.71891E-05	3.68102E-05	3.40518E-05	3.31614E-05	3.33801E-05	3.27443E-05	3.36684E-05	3.57202E-05	3.4796E-05
14	UPLOCK SWITCH		1424	249	1.3607E-05	1.39778E-05	1.44014E-05	1.42546E-05	1.31865E-05	1.28417E-05	1.29263E-05	1.26801E-05	1.3038E-05	1.38326E-05	1.3475E-05
15	V-BELT		1427	304	1.6613E-05	1.70652E-05	1.75824E-05	1.74033E-05	1.60991E-05	1.56782E-05	1.57816E-05	1.5481E-05	1.59179E-05	1.6888E-05	1.6451E-05
16	WARNING LIGHT		1464	414	2.2624E-05	2.32401E-05	2.39445E-05	2.37005E-05	2.19245E-05	2.13512E-05	2.1492E-05	2.10827E-05	2.16777E-05	2.29987E-05	2.2404E-05
17	WARNING SYSTEM		1466	296	1.6176E-05	1.66161E-05	1.71197E-05	1.69453E-05	1.56755E-05	1.52656E-05	1.53662E-05	1.50736E-05	1.5499E-05	1.64435E-05	1.6018E-05
18	WHEEL		1478	352	1.9236E-05	1.97597E-05	2.03586E-05	2.01511E-05	1.86411E-05	1.81537E-05	1.82734E-05	1.79253E-05	1.84312E-05	1.95545E-05	1.9048E-05
19	WIRE		1488	295	1.6121E-05	1.656E-05	1.70619E-05	1.6888E-05	1.56225E-05	1.5214E-05	1.53143E-05	1.50227E-05	1.54466E-05	1.6388E-05	1.5964E-05
20	WIRE HARNESS		1489	260	1.4208E-05	1.45953E-05	1.50376E-05	1.48844E-05	1.3769E-05	1.3409E-05	1.34974E-05	1.32403E-05	1.3614E-05	1.44436E-05	1.407E-05

Number of flight flown hours per year (millions)

Average difficulties rate

Appendix G Sequential evaluation of Allocation repair time

Table G-1 Sequential equation for allocation repair time [14]

No	Equations	Description
1	$k = \frac{\lambda jkj}{\lambda} + \cdots + \frac{\lambda pkp}{\lambda}$	*k = Weighting Factor* λ*j*, …….., λ*p* = failure rate of each unit λ = λ*j* + …… + λ*p* = failure rate of system/sub system
2	$\lambda = \frac{\lambda jkj}{k} + \cdots + \frac{\lambda pkp}{k}$	Solve for λ
3	$MTTR = \frac{\lambda jRpj}{\lambda} + \cdots + \frac{\lambda pRpp}{\lambda}$	Existing formula (known), where: λ*j*, …….., λ*p* = failure rate of each unit λ = λ*j* + …… + λ*p* = failure rate of system/sub system R*pj*, ……, R*pp* = Active repair time of each unit MTTR = Mean Time to Repair of system
4	$\lambda = \frac{\lambda jRpj}{MTTR} + \cdots + \frac{\lambda pRpp}{MTTR}$	Solve for λ
5	$\frac{\lambda jkj}{k} + \cdots + \frac{\lambda pkp}{k} = \frac{\lambda jRpj}{MTTR} + \cdots + \frac{\lambda pRpp}{MTTR}$	Therefore: equation (2) = (4)
6	$\lambda j \left(\frac{kj}{k} - \frac{Rpj}{MTTR}\right) + \ \ldots + \ \lambda p \left(\frac{kp}{k} - \frac{Rpp}{MTTR}\right) = 0$	Rearrange the equations (5)
7	$\left(\frac{kj}{k} - \frac{Rpj}{MTTR}\right) = 0$	Simplifies equation (6)
8	$\frac{kj}{k} = \frac{Rpj}{MTTR}$	Rearrange equation (7)
9	$Rpj = \frac{MTTR}{k} kj$	Equation to Allocated Active Repair (R*pj*)
10	$k = \frac{\sum_{j=1}^{n} \lambda jkj}{\Sigma \lambda}$	

Appendix H Testing and validating the four selected trendlines

Table H-1 List of initial maintainability allocation predictions

SEQ	TIME IN HOURS		SCORE
	FROM	TO	
1	0.000	0.526	1.0
2	0.527	1.053	1.5
3	1.054	1.579	2.0
4	1.580	2.105	2.5
5	2.106	2.632	3.0
6	2.633	3.158	3.5
7	3.159	3.684	4.0
8	3.685	4.211	4.5
9	4.212	4.737	5.0
10	4.738	5.263	5.5
11	5.264	5.789	6.0
12	5.790	6.316	6.5
13	6.317	6.842	7.0
14	6.843	7.368	7.5
15	7.369	7.895	8.0
16	7.896	8.421	8.5
17	8.422	8.947	9.0
18	8.948	9.474	9.5
19	9.475	10.000	10.0

Table H-2 List of maintainability allocation testing

No	TIME (HR)	SCORE	Vlookup	PREDICTION SCORE				Error			
				log	Linear	Power	Expon.	log	Linear	Power	Expon.
1	0.148	1.0	1.0	-0.7	2.0	0.9	2.0	-1.7	1.0	-0.1	1.0
2	0.532	1.0	1.5	2.6	2.5	2.2	2.2	1.6	1.5	1.2	1.2
3	0.532	1.5	1.5	2.6	2.5	2.2	2.2	1.1	1.0	0.7	0.7
4	0.532	1.5	1.5	2.6	2.5	2.2	2.2	1.1	1.0	0.7	0.7
5	0.378	2.0	1.0	1.7	2.3	1.7	2.1	-0.3	0.3	-0.3	0.1
6	0.336	2.0	1.0	1.4	2.3	1.6	2.1	-0.6	0.3	-0.4	0.1
7	1.074	3.0	2.0	4.4	3.3	3.5	2.7	1.4	0.3	0.5	-0.3
8	0.811	4.0	1.5	3.7	2.9	2.9	2.4	-0.3	-1.1	-1.1	-1.6
9	0.677	4.0	1.5	3.2	2.7	2.6	2.3	-0.8	-1.3	-1.4	-1.7
10	1.007	4.0	1.5	4.2	3.2	3.4	2.6	0.2	-0.8	-0.6	-1.4
11	1.130	4.0	2.0	4.5	3.4	3.7	2.7	0.5	-0.6	-0.3	-1.3
12	1.320	6.0	2.0	4.9	3.7	4.1	2.9	-1.1	-2.3	-1.9	-3.1
13	6.147	10.0	6.5	8.9	10.6	11.7	13.2	-1.1	0.6	1.7	3.2

Table H-3 Testing and validating by using EXISTING modules and score values

No	Unit	Generic Module Types	*Kj1*	*Kj2*	*Kj3*	Σ *Kj*	$F/10^{6}$ hours	*Fj Kj*	Allocated *Rpj*	FR * *Rpj*
1	Output TWT Power Supply	Power Supplies	2.0	0	0	2.0	776	1,552	0.72	555.56
2	Driver TWT and Auxiliary Power Supply	Power Supplies	2.0	0	0	2.0	1270	2,540	0.72	909.22
3	System Control Unit	Electromechanical+digital+electromechanical	2.3	0	0	2.3	368	859	0.84	307.37
4	Modulator Unit	Analog	1.5	0	0	1.5	282	423	0.54	151.42
5	Output TWT	High-power/High-frequency components	4.0	0	0	4.0	252	1,008	1.43	360.83
6	Driver TWT	High-power/High-frequency components	4.0	0	0	4.0	1300	5,200	1.43	1861.40
7	Antenna Drive	Eletromechanical equipment	3.0	0	0	3.0	682	2,046	1.07	732.39
8	Cooling pump/motor	Liquid coolant systems	4.0	0	0	4.0	120	480	1.43	171.82
							5,050	**14,108**		**5,050**

MTBF	198
MTTR	1.0
K	2.79
Rpj	0.3580
Check: MTTRsystem	1.0

Table H-4 Testing and validating by using LOG formula for new score values

No	Unit	Generic Module Types	*Kj1*	*Kj2*	*Kj3*	Σ *Kj*	$F/10^{6}$ hours	*Fj Kj*	Allocated *Rpj*	FR * *Rpj*
1	Output TWT Power Supply	Power Supplies	1.0	0	0	1.0	776	776	0.37	286.99
2	Driver TWT and Auxiliary Power Supply	Power Supplies	1.0	0	0	1.0	1270	1,270	0.37	469.69
3	System Control Unit	Electromechanical+digital+electromechanical	3.3	0	0	3.3	368	1,227	1.23	453.67
4	Modulator Unit	Analog	3.0	0	0	3.0	282	846	1.11	312.88
5	Output TWT	High-power/High-frequency components	4.0	0	0	4.0	252	1,008	1.48	372.80
6	Driver TWT	High-power/High-frequency components	4.0	0	0	4.0	1300	5,200	1.48	1923.15
7	Antenna Drive	Eletromechanical equipment	4.0	0	0	4.0	682	2,728	1.48	1008.92
8	Cooling pump/motor	Liquid coolant systems	5.0	0	0	5.0	120	600	1.85	221.90
							5,050	**13,655**		**5,050**

MTBF	198
MTTR	1.0
K	2.70
Rpj	0.3698
Check: MTTRsystem	1.0

Table H-5 Testing and validating by using LINEAR formula for new score values

No	Unit	Generic Module Types	*Kj1*	*Kj2*	*Kj3*	Σ *Kj*	$F/10^{6}$ hours	*Fj Kj*	Allocated *Rpj*	FR * *Rpj*
1	Output TWT Power Supply	Power Supplies	2.0	0	0	2.0	776	1,552	0.74	573.99
2	Driver TWT and Auxiliary Power Supply	Power Supplies	2.0	0	0	2.0	1270	2,540	0.74	939.39
3	System Control Unit	Electromechanical+digital+electromechanical	2.7	0	0	2.7	368	981	0.99	362.93
4	Modulator Unit	Analog	3.0	0	0	3.0	282	846	1.11	312.88
5	Output TWT	High-power/High-frequency components	3.0	0	0	3.0	252	756	1.11	279.60
6	Driver TWT	High-power/High-frequency components	3.0	0	0	3.0	1300	3,900	1.11	1442.36
7	Antenna Drive	Eletromechanical equipment	3.0	0	0	3.0	682	2,046	1.11	756.69
8	Cooling pump/motor	Liquid coolant systems	3.0	0	0	3.0	120	360	1.11	133.14
							5,050	**12,981**		**4,801**

MTBF	198
MTTR	1.0
K	2.57
Rpj	0.3890
Check: MTTRsystem	1.0

H.1 Test results summary

Table H-6 Summary the three different inputs

	Existing	Log	Linear
MTBF	198	198	198
MTTR	1	1	1
K	2.7936	2.7039	2.5706
Rpj	0.3580	0.3698	0.3890
Check: MTTRsystem	1.000	1.000	0.951

Table H-7 Summary of the three different outputs

No	Unit	Allocated Rpj		
		Existing	Log	Linear
1	Output TWT Power Supply	0.72	0.37	0.74
2	Driver TWT and Auxiliary Power Supply	0.72	0.37	0.74
3	System Control Unit	0.84	1.23	0.99
4	Modulator Unit	0.54	1.11	1.11
5	Output TWT	1.43	1.48	1.11
6	Driver TWT	1.43	1.48	1.11
7	Antenna Drive	1.07	1.48	1.11
8	Cooling pump/motor	1.43	1.85	1.11

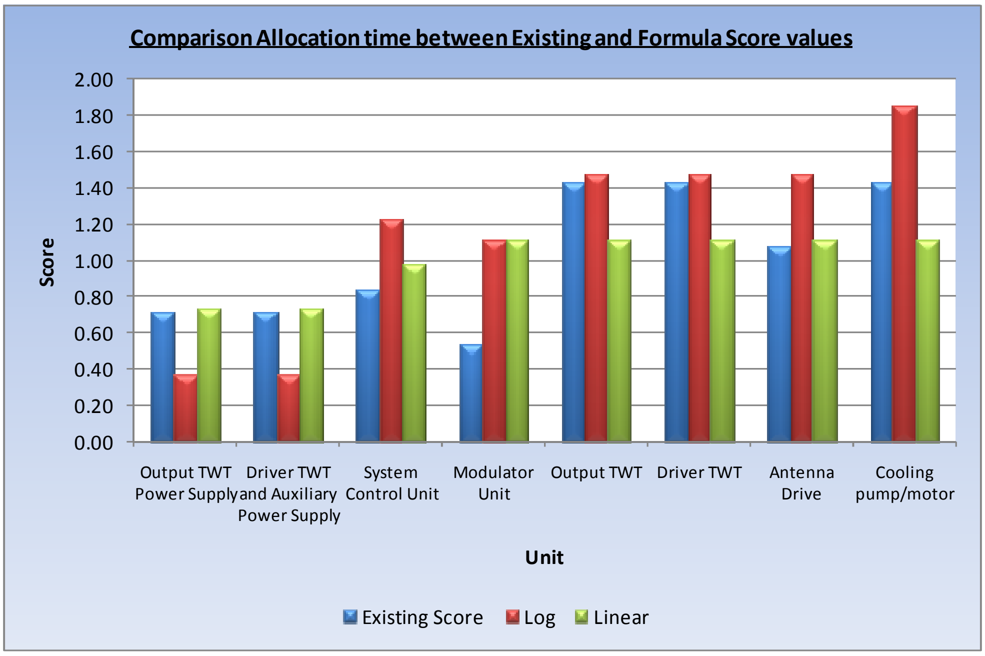

Figure H-1 Comparison of allocation time between existing score and two formulae

Appendix I Maintainability Allocation – Testing process

I.1 Case Study 1: Aircraft Fuel Systems

I.1.1 Existing Modules vs. Logarithmic Formula

Table I-1 Validation results using EXISTING modules and LOGARITHMIC score values

No	System / Sub System	Generic Module Types	FR (10-6 hour)				SCORE				FR*j* K*j*				Allocated R*pj*				FR * R*pj*			
		IAW New Allocation Scheme	1	2	3	4	K*j* 1	K*j* 2	K*j* 3	SUM	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	20.000	2.300	2.000	2.300	1.0	0.0	0.0	1.0	20.000	2.300	2.000	2.300	0.77	0.63	0.43	0.50	15.446	1.451	0.869	1.141
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	28.000	4.600	95.000	34.300	3.5	0.0	0.0	3.5	98.000	16.100	332.500	120.050	2.70	2.21	1.52	1.74	75.683	10.155	144.515	59.531
3	Pressure Valve (PV)	Interconnections +Electromechanical	28.000	5.600	25.100	2.900	3.5	0.0	0.0	3.5	98.000	19.600	87.850	10.150	2.70	2.21	1.52	1.74	75.683	12.362	38.182	5.033
4	Reservoir	Electromechanical + Power Supplies	0.130	0.128	618.000	0.128	2.5	0.0	0.0	2.5	0.325	0.320	1545.000	0.320	1.93	1.58	1.09	1.24	0.251	0.202	671.504	0.159
5	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.5	0.0	0.0	3.5	94.500	60.200	332.500	332.150	2.70	2.21	1.52	1.74	72.980	37.969	144.515	164.707
6	Engine Driven Pump (EDP)	Power Supplies	48.000	369.000	48.600	369.000	2.0	0.0	0.0	2.0	96.000	738.000	97.200	738.000	1.54	1.26	0.87	0.99	74.139	465.469	42.246	365.961
7	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.5	0.0	0.0	3.5	94.500	60.200	332.500	332.150	2.70	2.21	1.52	1.74	72.980	37.969	144.515	164.707
8	Aircraft Motor Pump (ACMP)	Power Supplies	8.200	16.900	36.900	16.900	1.0	0.0	0.0	1.0	8.200	16.900	36.900	16.900	0.77	0.63	0.43	0.50	6.333	10.659	16.038	8.380
9	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.5	0.0	0.0	3.5	94.500	60.200	332.500	332.150	2.70	2.21	1.52	1.74	72.980	37.969	144.515	164.707
10	Pipe	Interconnections	1.400	0.032	1.400	0.032	3.0	0.0	0.0	3.0	4.200	0.096	4.200	0.096	2.32	1.89	1.30	1.49	3.244	0.061	1.825	0.048
11	Pump Overheat Light (POL 1)	Lights	71.100	14.900	71.100	149.000	1.0	0.0	0.0	1.0	71.100	14.900	71.100	149.000	0.77	0.63	0.43	0.50	54.909	9.398	30.902	73.886
12	Pump Overheat Light (POL 2)	Lights	71.100	14.900	71.100	149.000	1.0	0.0	0.0	1.0	71.100	14.900	71.100	149.000	0.77	0.63	0.43	0.50	54.909	9.398	30.902	73.886
13	Pump Low Light (PLL 1)	Lights	605.000	39.800	71.100	39.800	1.0	0.0	0.0	1.0	605.000	39.800	71.100	39.800	0.77	0.63	0.43	0.50	467.229	25.103	30.902	19.736
14	Pump Low Light (PLL 2)	Lights	605.000	39.800	71.100	39.800	1.0	0.0	0.0	1.0	605.000	39.800	71.100	39.800	0.77	0.63	0.43	0.50	467.229	25.103	30.902	19.736
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.120	1.180	1.120	16.200	3.5	0.0	0.0	3.5	3.920	4.130	3.920	56.700	2.70	2.21	1.52	1.74	3.027	2.605	1.704	28.117
16	Hydraulic Low Light (HLL 1)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.77	0.63	0.43	0.50	241.723	93.977	64.760	73.886
17	Hydraulic Low Light (HLL 2)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.77	0.63	0.43	0.50	241.723	93.977	64.760	73.886
18	Hydraulic Low Light (HLL 3)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.77	0.63	0.43	0.50	241.723	93.977	64.760	73.886
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	15.000	6.040	71.200	71.200	3.5	0.0	0.0	3.5	52.500	21.140	249.200	249.200	2.70	2.21	1.52	1.74	40.545	13.333	108.310	123.574
20	Hose	Interconnections	11.000	11.600	116.000	116.000	3.0	0.0	0.0	3.0	33.000	34.800	348.000	348.000	2.32	1.89	1.30	1.49	25.485	21.949	151.251	172.567
21	Depressurisation Valve (DPV)	Interconnections +Electromechanical	107.000	1.280	107.000	1.280	3.5	0.0	0.0	3.5	374.500	4.480	374.500	4.480	2.70	2.21	1.52	1.74	289.218	2.826	162.769	2.222
22	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.5	0.0	0.0	3.5	94.500	60.200	332.500	332.150	2.70	2.21	1.52	1.74	72.980	37.969	144.515	164.707
23	Moisture Vent Trap (MVT)	Accessories	14.800	0.048	2.550	0.048	1.0	0.0	0.0	1.0	14.800	0.048	2.550	0.048	0.77	0.63	0.43	0.50	11.430	0.030	1.108	0.024
			2,681.850	**1,043.908**	**2,236.270**	**1,834.488**					**3,472.645**	**1,655.114**	**5,145.220**	**3,699.444**					**2,681.850**	**1,043.908**	**2,236.270**	**1,834.488**

LOG Formula

MTTR requirement	1.00	1.00	1.00	1.00
K Value	1.29	1.59	2.30	2.02
R*pj* = (MTTR/K)*K*j*	0.77	0.63	0.43	0.50
MTTR system	1.00	1.00	1.00	1.00

Table I-2 Validation results using IMPROVED modules and LOGARITHMIC score values

No	System / Sub System	Generic Module Types	FR (10-6 hour)				SCORE				FRj Kj				Allocated Rpj				FR * Rpj			
		IAW New Allocation Scheme	1	2	3	4	Kj 1	Kj 2	Kj 3	SUM	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	20.000	2.300	2.000	2.300	1.0	0.0	0.0	1.0	20.000	2.300	2.000	2.300	0.71	0.36	0.39	0.36	14.171	0.837	0.779	0.830
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	28.000	4.600	95.000	34.300	4.0	0.0	0.0	4.0	112.000	18.400	380.000	137.200	2.83	1.45	1.56	1.44	79.358	6.693	147.990	49.516
3	Pressure Valve (PV)	Valve	28.000	5.600	25.100	2.900	4.0	0.0	0.0	4.0	112.000	22.400	100.400	11.600	2.83	1.45	1.56	1.44	79.358	8.148	39.100	4.186
4	Reservoir	Electromechanical + Power Supplies	0.130	0.128	618.000	0.128	2.5	0.0	0.0	2.5	0.325	0.320	1545.000	0.320	1.77	0.91	0.97	0.90	0.230	0.116	601.695	0.115
5	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	4.0	0.0	0.0	4.0	108.000	68.800	380.000	379.600	2.83	1.45	1.56	1.44	76.524	25.026	147.990	136.998
6	Engine Driven Pump (EDP)	Pump	48.000	369.000	48.600	369.000	5.0	0.0	0.0	5.0	240.000	1845.000	243.000	1845.000	3.54	1.82	1.95	1.80	170.054	671.118	94.636	665.862
7	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	4.0	0.0	0.0	4.0	108.000	68.800	380.000	379.600	2.83	1.45	1.56	1.44	76.524	25.026	147.990	136.998
8	Aircraft Motor Pump (ACMP)	Pump	8.200	16.900	36.900	16.900	5.0	0.0	0.0	5.0	41.000	84.500	184.500	84.500	3.54	1.82	1.95	1.80	29.051	30.737	71.853	30.496
9	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	4.0	0.0	0.0	4.0	108.000	68.800	380.000	379.600	2.83	1.45	1.56	1.44	76.524	25.026	147.990	136.998
10	Pipe	Pipe	1.400	0.032	1.400	0.032	3.0	0.0	0.0	3.0	4.200	0.096	4.200	0.096	2.13	1.09	1.17	1.08	2.976	0.035	1.636	0.035
11	Pump Overheat Light (POL 1)	Lights	71.100	14.900	71.100	149.000	1.0	0.0	0.0	1.0	71.100	14.900	71.100	149.000	0.71	0.36	0.39	0.36	50.378	5.420	27.690	53.774
12	Pump Overheat Light (POL 2)	Lights	71.100	14.900	71.100	149.000	1.0	0.0	0.0	1.0	71.100	14.900	71.100	149.000	0.71	0.36	0.39	0.36	50.378	5.420	27.690	53.774
13	Pump Low Light (PLL 1)	Lights	605.000	39.800	71.100	39.800	1.0	0.0	0.0	1.0	605.000	39.800	71.100	39.800	0.71	0.36	0.39	0.36	428.677	14.477	27.690	14.364
14	Pump Low Light (PLL 2)	Lights	605.000	39.800	71.100	39.800	1.0	0.0	0.0	1.0	605.000	39.800	71.100	39.800	0.71	0.36	0.39	0.36	428.677	14.477	27.690	14.364
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.120	1.180	1.120	16.200	3.5	0.0	0.0	3.5	3.920	4.130	3.920	56.700	2.48	1.27	1.36	1.26	2.778	1.502	1.527	20.463
16	Hydraulic Low Light (HLL 1)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.71	0.36	0.39	0.36	221.778	54.199	58.028	53.774
17	Hydraulic Low Light (HLL 2)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.71	0.36	0.39	0.36	221.778	54.199	58.028	53.774
18	Hydraulic Low Light (HLL 3)	Lights	313.000	149.000	149.000	149.000	1.0	0.0	0.0	1.0	313.000	149.000	149.000	149.000	0.71	0.36	0.39	0.36	221.778	54.199	58.028	53.774
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	15.000	6.040	71.200	71.200	3.5	0.0	0.0	3.5	52.500	21.140	249.200	249.200	2.48	1.27	1.36	1.26	37.199	7.690	97.050	89.936
20	Hose	Interconnections	11.000	11.600	116.000	116.000	3.0	0.0	0.0	3.0	33.000	34.800	348.000	348.000	2.13	1.09	1.17	1.08	23.382	12.658	135.528	125.593
21	Depressurisation Valve (DPV)	Valve	107.000	1.280	107.000	1.280	4.0	0.0	0.0	4.0	428.000	5.120	428.000	5.120	2.83	1.45	1.56	1.44	303.262	1.862	166.683	1.848
22	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	4.0	0.0	0.0	4.0	108.000	68.800	380.000	379.600	2.83	1.45	1.56	1.44	76.524	25.026	147.990	136.998
23	Moisture Vent Trap (MVT)	Accessories	14.800	0.048	2.550	0.048	1.0	0.0	0.0	1.0	14.800	0.048	2.550	0.048	0.71	0.36	0.39	0.36	10.487	0.017	0.993	0.017
			2,681.850	**1,043.908**	**2,236.270**	**1,834.488**					**3,784.945**	**2,869.854**	**5,742.170**	**5,083.084**					**2,681.850**	**1,043.908**	**2,236.270**	**1,834.488**

LOG Formula

MTTR requirement	1.00	1.00	1.00	1.00
K Value	1.41	2.75	2.57	2.77
Rpj = $(MTTR/K)$*Kj	0.71	0.36	0.39	0.36
MTTR system	1.00	1.00	1.00	1.00

Table I-3 Validation summary by using EXISTING modules and LOGARITHMIC score values

No	System / Sub System	Generic Module Types	Allocation (Existing)				Allocation (LOG Formula)				Absolute Error (LOG Formula - Existing)			
		IAW New Allocation Scheme	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	2.34	1.57	1.77	1.62	0.77	0.63	0.43	0.50	1.56	0.94	1.33	1.12
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
3	Pressure Valve (PV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
4	Reservoir	Electromechanical + Power Supplies	1.31	0.88	0.99	0.91	1.93	1.58	1.09	1.24	0.62	0.69	0.09	0.33
5	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
6	Engine Driven Pump (EDP)	Power Supplies	2.34	1.57	1.77	1.62	1.54	1.26	0.87	0.99	0.79	0.31	0.90	0.63
7	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
8	Aircraft Motor Pump (ACMP)	Power Supplies	2.34	1.57	1.77	1.62	0.77	0.63	0.43	0.50	1.56	0.94	1.33	1.12
9	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
10	Pipe	Interconnections	1.75	1.18	1.33	1.22	2.32	1.89	1.30	1.49	0.56	0.72	0.02	0.27
11	Pump Overheat Light (POL 1)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
12	Pump Overheat Light (POL 2)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
13	Pump Low Light (PLL 1)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
14	Pump Low Light (PLL 2)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
16	Hydraulic Low Light (HLL 1)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
17	Hydraulic Low Light (HLL 2)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
18	Hydraulic Low Light (HLL 3)	Lights	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
20	Hose	Interconnections	1.75	1.18	1.33	1.22	2.32	1.89	1.30	1.49	0.56	0.72	0.02	0.27
21	Depressurisation Valve (DPV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
22	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.70	2.21	1.52	1.74	1.10	1.13	0.31	0.62
23	Moisture Vent Trap (MVT)	Accessories	0.88	0.59	0.66	0.61	0.77	0.63	0.43	0.50	0.10	0.04	0.23	0.11

	1	2	3	4
Σ Mean Absolute Error	0.71	0.64	0.36	0.45
	8.00	9.00	20.00	11.00
Percentage (%)	34.78%	39.13%	86.96%	47.83%

Average on MEAN Absolute Error	0.54
Average on Percentage	52.17%

Table I-4 Validation summary by using IMPROVED modules and LOGARITHMIC score values

No	System / Sub System	Generic Module Types	Allocation (Existing)				Allocation (LOG Formula)				Absolute Error (LOG Formula - Existing)			
		IAW New Allocation Scheme	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	2.34	1.57	1.77	1.62	0.71	0.36	0.39	0.36	1.63	1.20	1.38	1.26
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
3	Pressure Valve (PV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
4	Reservoir	Electromechanical + Power Supplies	1.31	0.88	0.99	0.91	1.77	0.91	0.97	0.90	0.46	0.03	0.02	0.01
5	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
6	Engine Driven Pump (EDP)	Pump	2.34	1.57	1.77	1.62	3.54	1.82	1.95	1.80	1.21	0.25	0.18	0.18
7	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
8	Aircraft Motor Pump (ACMP)	Pump	2.34	1.57	1.77	1.62	3.54	1.82	1.95	1.80	1.21	0.25	0.18	0.18
9	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
10	Pipe	Pipe	1.75	1.18	1.33	1.22	2.13	1.09	1.17	1.08	0.37	0.08	0.16	0.13
11	Pump Overheat Light (POL 1)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
12	Pump Overheat Light (POL 2)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
13	Pump Low Light (PLL 1)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
14	Pump Low Light (PLL 2)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.48	1.27	1.36	1.26	0.87	0.20	0.15	0.15
16	Hydraulic Low Light (HLL 1)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
17	Hydraulic Low Light (HLL 2)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
18	Hydraulic Low Light (HLL 3)	Lights	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	2.48	1.27	1.36	1.26	0.87	0.20	0.15	0.15
20	Hose	Interconnections	1.75	1.18	1.33	1.22	2.13	1.09	1.17	1.08	0.37	0.08	0.16	0.13
21	Depressurisation Valve (DPV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
22	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	2.83	1.45	1.56	1.44	1.23	0.38	0.34	0.33
23	Moisture Vent Trap (MVT)	Accessories	0.88	0.59	0.66	0.61	0.71	0.36	0.39	0.36	0.17	0.22	0.27	0.25

	1	2	3	4
Σ Mean Absolute Error	0.74	0.29	0.30	0.28
	11.00	22.00	22.00	22.00
Percentage (%)	47.83%	95.65%	95.65%	95.65%

Average on MEAN Absolute Error	0.40
Average on Percentage	83.70%

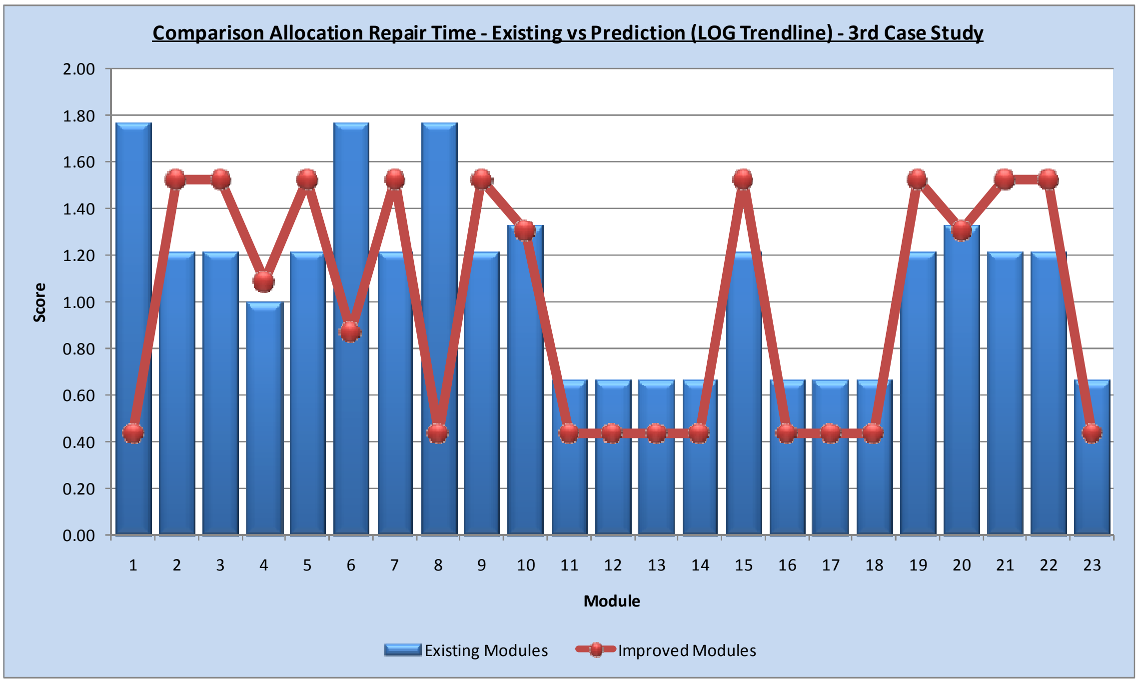

Figure I-1 Summary results by using EXISTING modules for 3rd Failure Rate

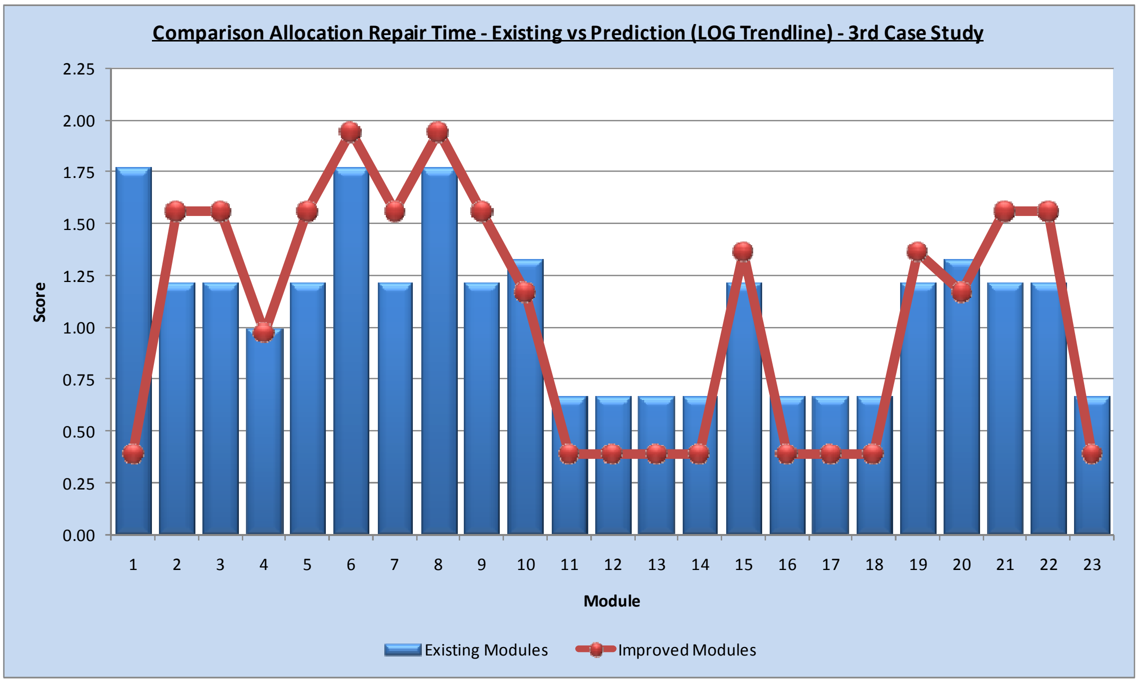

Figure I-2 Summary results by using IMPROVED modules and score values for 3rd Failure Rate

I.1.2 Existing Modules vs. Linear Formula

Table I-5 Validation results using EXISTING modules and LINEAR score values

No	System / Sub System	Generic Module Types	FR (10-6 hour)				SCORE				FR*j* K*j*				Allocated R*pj*				FR * R*pj*			
		IAW New Allocation Scheme	1	2	3	4	K*j* 1	K*j* 2	K*j* 3	SUM	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	20.000	2.300	2.000	2.300	2.0	0.0	0.0	2.0	40.000	4.600	4.000	4.600	0.95	0.95	0.80	0.86	18.942	2.196	1.604	1.967
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	28.000	4.600	95.000	34.300	3.0	0.0	0.0	3.0	84.000	13.800	285.000	102.900	1.42	1.43	1.20	1.28	39.778	6.587	114.252	43.996
3	Pressure Valve (PV)	Interconnections +Electromechanical	28.000	5.600	25.100	2.900	3.0	0.0	0.0	3.0	84.000	16.800	75.300	8.700	1.42	1.43	1.20	1.28	39.778	8.019	30.186	3.720
4	Reservoir	Electromechanical + Power Supplies	0.130	0.128	618.000	0.128	2.5	0.0	0.0	2.5	0.325	0.320	1545.000	0.320	1.18	1.19	1.00	1.07	0.154	0.153	619.364	0.137
5	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.42	1.43	1.20	1.28	38.358	24.630	114.252	121.728
6	Engine Driven Pump (EDP)	Power Supplies	48.000	369.000	48.600	369.000	2.0	0.0	0.0	2.0	96.000	738.000	97.200	738.000	0.95	0.95	0.80	0.86	45.461	352.263	38.966	315.543
7	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.42	1.43	1.20	1.28	38.358	24.630	114.252	121.728
8	Aircraft Motor Pump (ACMP)	Power Supplies	8.200	16.900	36.900	16.900	2.0	0.0	0.0	2.0	16.400	33.800	73.800	33.800	0.95	0.95	0.80	0.86	7.766	16.133	29.585	14.452
9	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.42	1.43	1.20	1.28	38.358	24.630	114.252	121.728
10	Pipe	Interconnections	1.400	0.032	1.400	0.032	3.0	0.0	0.0	3.0	4.200	0.096	4.200	0.096	1.42	1.43	1.20	1.28	1.989	0.046	1.684	0.041
11	Pump Overheat Light (POL 1)	Lights	71.100	14.900	71.100	149.000	2.0	0.0	0.0	2.0	142.200	29.800	142.200	298.000	0.95	0.95	0.80	0.86	67.339	14.224	57.006	127.414
12	Pump Overheat Light (POL 2)	Lights	71.100	14.900	71.100	149.000	2.0	0.0	0.0	2.0	142.200	29.800	142.200	298.000	0.95	0.95	0.80	0.86	67.339	14.224	57.006	127.414
13	Pump Low Light (PLL 1)	Lights	605.000	39.800	71.100	39.800	2.0	0.0	0.0	2.0	1210.000	79.600	142.200	79.600	0.95	0.95	0.80	0.86	572.996	37.995	57.006	34.034
14	Pump Low Light (PLL 2)	Lights	605.000	39.800	71.100	39.800	2.0	0.0	0.0	2.0	1210.000	79.600	142.200	79.600	0.95	0.95	0.80	0.86	572.996	37.995	57.006	34.034
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.120	1.180	1.120	16.200	3.0	0.0	0.0	3.0	3.360	3.540	3.360	48.600	1.42	1.43	1.20	1.28	1.591	1.690	1.347	20.780
16	Hydraulic Low Light (HLL 1)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.95	0.95	0.80	0.86	296.442	142.242	119.463	127.414
17	Hydraulic Low Light (HLL 2)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.95	0.95	0.80	0.86	296.442	142.242	119.463	127.414
18	Hydraulic Low Light (HLL 3)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.95	0.95	0.80	0.86	296.442	142.242	119.463	127.414
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	15.000	6.040	71.200	71.200	3.0	0.0	0.0	3.0	45.000	18.120	213.600	213.600	1.42	1.43	1.20	1.28	21.310	8.649	85.629	91.328
20	Hose	Interconnections	11.000	11.600	116.000	116.000	3.0	0.0	0.0	3.0	33.000	34.800	348.000	348.000	1.42	1.43	1.20	1.28	15.627	16.611	139.507	148.792
21	Depressurisation Valve (DPV)	Interconnections +Electromechanical	107.000	1.280	107.000	1.280	3.0	0.0	0.0	3.0	321.000	3.840	321.000	3.840	1.42	1.43	1.20	1.28	152.010	1.833	128.683	1.642
22	Non Return Valve (NRV)	Interconnections +Electromechanical	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.42	1.43	1.20	1.28	38.358	24.630	114.252	121.728
23	Moisture Vent Trap (MVT)	Accessories	14.800	0.048	2.550	0.048	2.0	0.0	0.0	2.0	29.600	0.096	5.100	0.096	0.95	0.95	0.80	0.86	14.017	0.046	2.045	0.041
			2,681.850	**1,043.908**	**2,236.270**	**1,834.488**					**5,663.285**	**2,187.012**	**5,578.360**	**4,290.552**					**2,681.850**	**1,043.908**	**2,236.270**	**1,834.488**

LINEAR Formula

MTTR requirement	1.00	1.00	1.00	1.00
K Value	2.11	2.10	2.49	2.34
R*pj* = (MTTR/K)*K*j*	0.47	0.48	0.40	0.43
MTTR system	1.00	1.00	1.00	1.00

Table I-6 Validation results using IMPROVED modules and LINEAR score values

No	System / Sub System	Generic Module Types	FR (10-6 hour)				SCORE				FR*j* K*j*				Allocated R*pj*				FR * R*pj*			
		IAW New Allocation Scheme	1	2	3	4	K*j* 1	K*j* 2	K*j* 3	SUM	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	20.000	2.300	2.000	2.300	2.0	0.0	0.0	2.0	40.000	4.600	4.000	4.600	0.94	0.81	0.79	0.78	18.756	1.866	1.579	1.804
2	Reservoir Fill Selection Valve (RFSV)	Valve	28.000	4.600	95.000	34.300	3.0	0.0	0.0	3.0	84.000	13.800	285.000	102.900	1.41	1.22	1.18	1.18	39.387	5.599	112.527	40.366
3	Pressure Valve (PV)	Valve	28.000	5.600	25.100	2.900	3.0	0.0	0.0	3.0	84.000	16.800	75.300	8.700	1.41	1.22	1.18	1.18	39.387	6.816	29.731	3.413
4	Reservoir	Electromechanical + Power Supplies	0.130	0.128	618.000	0.128	2.5	0.0	0.0	2.5	0.325	0.320	1545.000	0.320	1.17	1.01	0.99	0.98	0.152	0.130	610.015	0.126
5	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.41	1.22	1.18	1.18	37.981	20.936	112.527	111.683
6	Engine Driven Pump (EDP)	Pump	48.000	369.000	48.600	369.000	3.0	0.0	0.0	3.0	144.000	1107.000	145.800	1107.000	1.41	1.22	1.18	1.18	67.521	449.143	57.566	434.256
7	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.41	1.22	1.18	1.18	37.981	20.936	112.527	111.683
8	Aircraft Motor Pump (ACMP)	Pump	8.200	16.900	36.900	16.900	3.0	0.0	0.0	3.0	24.600	50.700	110.700	50.700	1.41	1.22	1.18	1.18	11.535	20.571	43.708	19.889
9	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.41	1.22	1.18	1.18	37.981	20.936	112.527	111.683
10	Pipe	Pipe	1.400	0.032	1.400	0.032	3.0	0.0	0.0	3.0	4.200	0.096	4.200	0.096	1.41	1.22	1.18	1.18	1.969	0.039	1.658	0.038
11	Pump Overheat Light (POL 1)	Lights	71.100	14.900	71.100	149.000	2.0	0.0	0.0	2.0	142.200	29.800	142.200	298.000	0.94	0.81	0.79	0.78	66.677	12.091	56.145	116.900
12	Pump Overheat Light (POL 2)	Lights	71.100	14.900	71.100	149.000	2.0	0.0	0.0	2.0	142.200	29.800	142.200	298.000	0.94	0.81	0.79	0.78	66.677	12.091	56.145	116.900
13	Pump Low Light (PLL 1)	Lights	605.000	39.800	71.100	39.800	2.0	0.0	0.0	2.0	1210.000	79.600	142.200	79.600	0.94	0.81	0.79	0.78	567.366	32.296	56.145	31.226
14	Pump Low Light (PLL 2)	Lights	605.000	39.800	71.100	39.800	2.0	0.0	0.0	2.0	1210.000	79.600	142.200	79.600	0.94	0.81	0.79	0.78	567.366	32.296	56.145	31.226
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.120	1.180	1.120	16.200	3.0	0.0	0.0	3.0	3.360	3.540	3.360	48.600	1.41	1.22	1.18	1.18	1.575	1.436	1.327	19.065
16	Hydraulic Low Light (HLL 1)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.94	0.81	0.79	0.78	293.530	120.908	117.660	116.900
17	Hydraulic Low Light (HLL 2)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.94	0.81	0.79	0.78	293.530	120.908	117.660	116.900
18	Hydraulic Low Light (HLL 3)	Lights	313.000	149.000	149.000	149.000	2.0	0.0	0.0	2.0	626.000	298.000	298.000	298.000	0.94	0.81	0.79	0.78	293.530	120.908	117.660	116.900
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	15.000	6.040	71.200	71.200	3.0	0.0	0.0	3.0	45.000	18.120	213.600	213.600	1.41	1.22	1.18	1.18	21.100	7.352	84.336	83.791
20	Hose	Interconnections	11.000	11.600	116.000	116.000	3.0	0.0	0.0	3.0	33.000	34.800	348.000	348.000	1.41	1.22	1.18	1.18	15.474	14.119	137.401	136.514
21	Depressurisation Valve (DPV)	Valve	107.000	1.280	107.000	1.280	3.0	0.0	0.0	3.0	321.000	3.840	321.000	3.840	1.41	1.22	1.18	1.18	150.516	1.558	126.741	1.506
22	Non Return Valve (NRV)	Valve	27.000	17.200	95.000	94.900	3.0	0.0	0.0	3.0	81.000	51.600	285.000	284.700	1.41	1.22	1.18	1.18	37.981	20.936	112.527	111.683
23	Moisture Vent Trap (MVT)	Accessories	14.800	0.048	2.550	0.048	2.0	0.0	0.0	2.0	29.600	0.096	5.100	0.096	0.94	0.81	0.79	0.78	13.879	0.039	2.014	0.038
			2,681.850	**1,043.908**	**2,236.270**	**1,834.488**					**5,719.485**	**2,572.912**	**5,663.860**	**4,676.452**					**2,681.850**	**1,043.908**	**2,236.270**	**1,834.488**

LINEAR Formula

MTTR requirement	1.00	1.00	1.00	1.00
K Value	2.13	2.46	2.53	2.55
R*pj* = *(MTTR/K)**K*j*	0.47	0.41	0.39	0.39
MTTR system	1.00	1.00	1.00	1.00

Table I-7 Validation summary by using EXISTING modules and LINEAR score values

No	System / Sub System	Generic Module Types	Allocation (Existing)				Allocation (LINEAR Formula)				Absolute Error (Linear Formula - Existing)			
		IAW New Allocation Scheme	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	2.34	1.57	1.77	1.62	0.95	0.95	0.80	0.86	1.39	0.61	0.97	0.77
2	Reservoir Fill Selection Valve (RFSV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
3	Pressure Valve (PV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
4	Reservoir	Electromechanical + Power Supplies	1.31	0.88	0.99	0.91	1.18	1.19	1.00	1.07	0.13	0.31	0.01	0.16
5	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
6	Engine Driven Pump (EDP)	Power Supplies	2.34	1.57	1.77	1.62	0.95	0.95	0.80	0.86	1.39	0.61	0.97	0.77
7	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
8	Aircraft Motor Pump (ACMP)	Power Supplies	2.34	1.57	1.77	1.62	0.95	0.95	0.80	0.86	1.39	0.61	0.97	0.77
9	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
10	Pipe	Interconnections	1.75	1.18	1.33	1.22	1.42	1.43	1.20	1.28	0.33	0.26	0.12	0.07
11	Pump Overheat Light (POL 1)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
12	Pump Overheat Light (POL 2)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
13	Pump Low Light (PLL 1)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
14	Pump Low Light (PLL 2)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
16	Hydraulic Low Light (HLL 1)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
17	Hydraulic Low Light (HLL 2)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
18	Hydraulic Low Light (HLL 3)	Lights	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
20	Hose	Interconnections	1.75	1.18	1.33	1.22	1.42	1.43	1.20	1.28	0.33	0.26	0.12	0.07
21	Depressurisation Valve (DPV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
22	Non Return Valve (NRV)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.42	1.43	1.20	1.28	0.19	0.35	0.01	0.17
23	Moisture Vent Trap (MVT)	Accessories	0.88	0.59	0.66	0.61	0.95	0.95	0.80	0.86	0.07	0.37	0.14	0.25

	1	2	3	4
Σ MEAN Absolute Error	0.31	0.38	0.19	0.26
	20.00	20.00	20.00	20.00
Percentage (%)	86.96%	86.96%	86.96%	86.96%

Average on MEAN Absolute Error	0.29
Average on Percentage	86.96%

Table I-8 Validation summary by using IMPROVED modules and LINEAR score values

No	System / Sub System	Generic Module Types	Allocation (Existing)				Allocation (LINEAR Formula)				Absolute Error (Linear Formula - Existing)			
		IAW New Allocation Scheme	1	2	3	4	1	2	3	4	1	2	3	4
1	Hand Pump	Power Supplies	2.34	1.57	1.77	1.62	0.94	0.81	0.79	0.78	1.40	0.76	0.98	0.84
2	Reservoir Fill Selection Valve (RFSV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
3	Pressure Valve (PV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
4	Reservoir	Electromechanical + Power Supplies	1.31	0.88	0.99	0.91	1.17	1.01	0.99	0.98	0.14	0.13	0.01	0.07
5	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
6	Engine Driven Pump (EDP)	Pump	2.34	1.57	1.77	1.62	1.41	1.22	1.18	1.18	0.93	0.35	0.58	0.44
7	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
8	Aircraft Motor Pump (ACMP)	Pump	2.34	1.57	1.77	1.62	1.41	1.22	1.18	1.18	0.93	0.35	0.58	0.44
9	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
10	Pipe	Pipe	1.75	1.18	1.33	1.22	1.41	1.22	1.18	1.18	0.35	0.04	0.14	0.04
11	Pump Overheat Light (POL 1)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
12	Pump Overheat Light (POL 2)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
13	Pump Low Light (PLL 1)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
14	Pump Low Light (PLL 2)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
15	Heat Exchanger (HEX)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
16	Hydraulic Low Light (HLL 1)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
17	Hydraulic Low Light (HLL 2)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
18	Hydraulic Low Light (HLL 3)	Lights	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18
19	Hydraulic Quantity Indicator (HQ 1)	Interconnections +Electromechanical	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
20	Hose	Interconnections	1.75	1.18	1.33	1.22	1.41	1.22	1.18	1.18	0.35	0.04	0.14	0.04
21	Depressurisation Valve (DPV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
22	Non Return Valve (NRV)	Valve	1.61	1.08	1.21	1.11	1.41	1.22	1.18	1.18	0.20	0.14	0.03	0.06
23	Moisture Vent Trap (MVT)	Accessories	0.88	0.59	0.66	0.61	0.94	0.81	0.79	0.78	0.06	0.22	0.13	0.18

	1	2	3	4
Σ MEAN Absolute Error	0.28	0.20	0.16	0.17
	20.00	22.00	20.00	22.00
Percentage (%)	86.96%	95.65%	86.96%	95.65%

Average on MEAN Absolute Error	0.20
Average on Percentage	91.30%

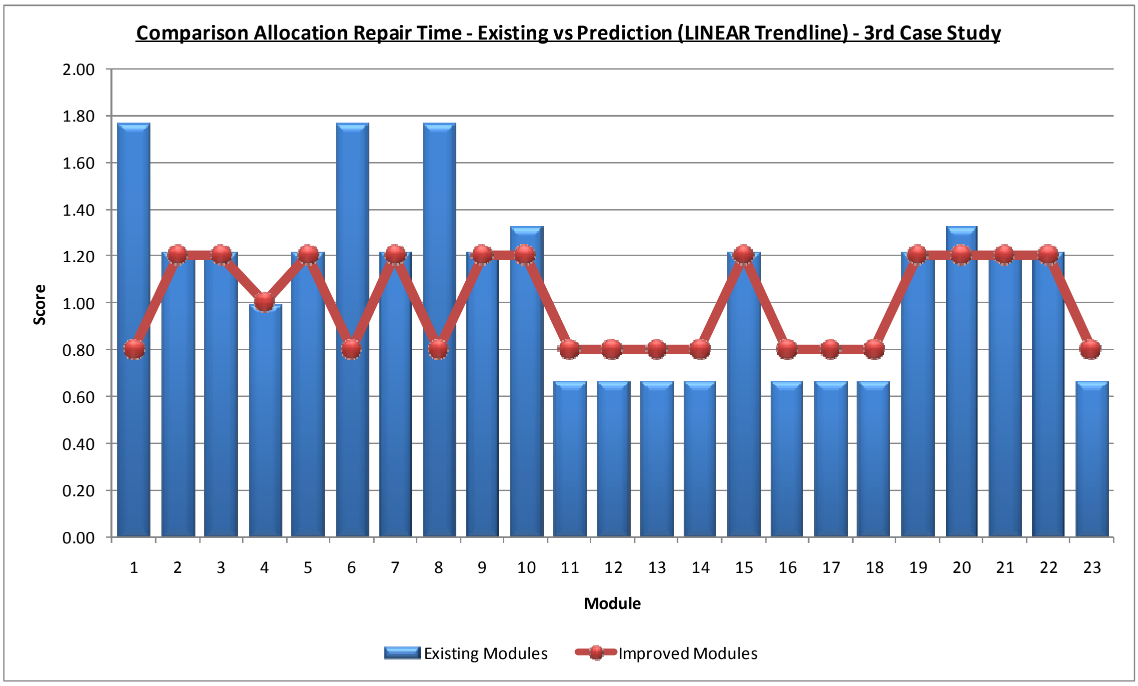

Figure I-3 Summary results by using EXISTING modules

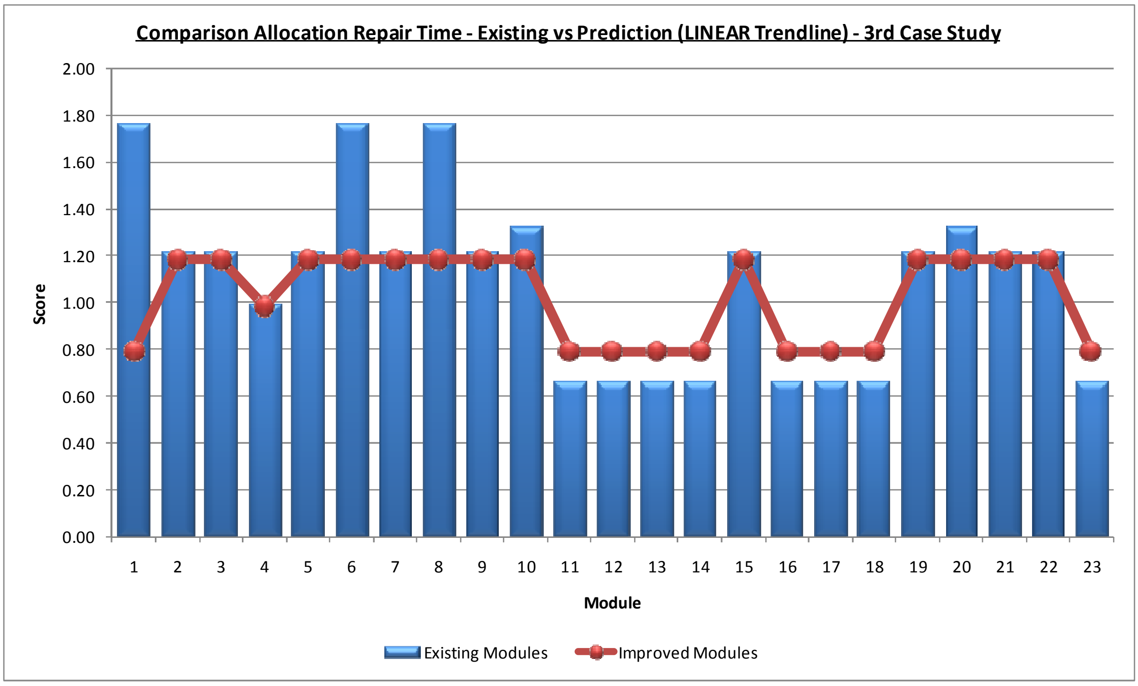

Figure I-4 Summary results by using IMPROVED modules and score values

I.2 Case Study 2: Aircraft Communication Systems

Table I-9 Validation results by using EXISTING modules and score values

No	System / Sub System	Generic Module Types	λ 10^{-6} hour	SCORE $Kj1$	$Kj2$	$Kj3$	ΣKj	Σ λMi	Allocated R_{pj} (hour)	Σ λR_{pj}
1	Audio Selector Panel 1	High-level analogue	166.805	1.5	0.0	0.0	3.0	500	0.72	120.4
2	Audio Selector Panel 2	High-level analogue	166.805	1.5	0.0	0.0	3.5	584	0.84	140.5
3	Headset 1	Communication	156.400	2.0	0.0	0.0	4.0	626	0.96	150.5
4	Headset 2	Communication	156.400	2.0	0.0	0.0	4.0	626	0.96	150.5
5	Handheld Microphone 1	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.96	342.4
6	Handheld Microphone 2	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.96	342.4
7	Speaker 1	Communication	47.460	2.0	0.0	0.0	4.0	190	0.96	45.7
8	Speaker 2	Communication	47.460	2.0	0.0	0.0	6.0	285	1.44	68.5
9	VHF 1 Antenna	High-power/high-frequency components	10.758	4.0	0.0	0.0	4.0	43	0.96	10.4
10	VHF 1 Transceiver	High-power/high-frequency components	60.000	4.0	0.0	0.0	4.0	240	0.96	57.7
11	VHF 1 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.48	51.3
12	VHF 2 Antenna	High-power/high-frequency components	10.758	4.0	0.0	0.0	4.0	43	0.96	10.4
13	VHF 2 Transceiver	High-power/high-frequency components	60.000	4.0	0.0	0.0	4.0	240	0.96	57.7
14	VHF 2 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.48	51.3
15	HF Antenna	High-power/high-frequency components	33.100	4.0	0.0	0.0	4.0	132	0.96	31.9
16	HF Lightning Arrestor	Lights	23.814	1.0	0.0	0.0	1.0	24	0.24	5.7
17	HF Antenna Coupler	High-power/high-frequency components	96.089	4.0	0.0	0.0	4.0	384	0.96	92.5
18	HF Transceiver	High-power/high-frequency components	58.338	4.0	0.0	0.0	4.0	233	0.96	56.1
19	HF Control Panel	Digital Computer	11.775	2.0	0.0	0.0	2.0	24	0.48	5.7
20	Selcal Decoder	High-power/high-frequency components	24.675	4.0	0.0	0.0	4.0	99	0.96	23.7
21	Selcal Control Panel	Digital Computer	72.384	2.0	0.0	0.0	2.0	145	0.48	34.8
22	Passenger Address Amplifier 1	High-power/high-frequency components	139.992	4.0	0.0	0.0	8.0	1,120	1.92	269.5
23	Passenger Address Amplifier 2	High-power/high-frequency components	139.992	4.0	0.0	0.0	8.0	1,120	1.92	269.5
24	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.92	87.2
25	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.92	87.2
26	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.92	87.2
27	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	6.0	272	1.44	65.4
28	Cockpit Voice Recorder Control Panel	Digital Computer	26.000	2.0	0.0	0.0	2.0	52	0.48	12.5
29	Cockpit Voice Recorder	Digital	150.000	1.0	0.0	0.0	1.0	150	0.24	36.1
	TOTAL (Σ)		2,765					11,490		2,765

MTTR Requirement (hour) 1.00

$M_{system} = \dfrac{\Sigma \lambda M_i}{\lambda} = \dfrac{11,490}{2,765} = \boxed{4.16}$

$(Rpj = (MTTR/M_{system})Mi = R_{pj} = \dfrac{MTTR}{M_{system}} = \dfrac{1.00}{4.16} = \boxed{0.2406}$

Therefore: Allocated Active Repair Time (R_{pj}) = $\boxed{0.2406} \times M_i$

To check MTTR REQUIREMENT (HOUR) $\dfrac{\Sigma \lambda R_{pj}}{\Sigma \lambda} = \dfrac{2,765}{2,765} = \boxed{1.00}$ **PASSED**

Table I-10 Validation results by using LOGARITHMIC formula for new score values

No	System / Sub System	Generic Module Types	λ	SCORE (LOG)			ΣKj	Σ	Allocated	Σ
			10^{-6} hour	Kj 1	Kj 2	Kj 3		λKj	R_{pj} (hour)	λR_{pj}
1	Audio Selector Panel 1	High-level analogue	166.805	3.0	0.0	0.0	6.0	1,001	1.32	220.6
2	Audio Selector Panel 2	High-level analogue	166.805	3.0	0.0	0.0	5.0	834	1.10	183.9
3	Headset 1	Communication	156.400	2.0	0.0	0.0	4.0	626	0.88	137.9
4	Headset 2	Communication	156.400	2.0	0.0	0.0	4.0	626	0.88	137.9
5	Handheld Microphone 1	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.88	313.7
6	Handheld Microphone 2	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.88	313.7
7	Speaker 1	Communication	47.460	2.0	0.0	0.0	4.0	190	0.88	41.9
8	Speaker 2	Communication	47.460	2.0	0.0	0.0	6.0	285	1.32	62.8
9	VHF 1 Antenna	High-power/high-frequency components	10.758	4.0	0.0	0.0	4.0	43	0.88	9.5
10	VHF 1 Transceiver	High-power/high-frequency components	60.000	4.0	0.0	0.0	4.0	240	0.88	52.9
11	VHF 1 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.44	47.0
12	VHF 2 Antenna	High-power/high-frequency components	10.758	4.0	0.0	0.0	4.0	43	0.88	9.5
13	VHF 2 Transceiver	High-power/high-frequency components	60.000	4.0	0.0	0.0	4.0	240	0.88	52.9
14	VHF 2 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.44	47.0
15	HF Antenna	High-power/high-frequency components	33.100	4.0	0.0	0.0	4.0	132	0.88	29.2
16	HF Lightning Arrestor	Lights	23.814	1.0	0.0	0.0	1.0	24	0.22	5.3
17	HF Antenna Coupler	High-power/high-frequency components	96.089	4.0	0.0	0.0	4.0	384	0.88	84.7
18	HF Transceiver	High-power/high-frequency components	58.338	4.0	0.0	0.0	4.0	233	0.88	51.4
19	HF Control Panel	Digital Computer	11.775	2.0	0.0	0.0	2.0	24	0.44	5.2
20	Selcal Decoder	High-power/high-frequency components	24.675	4.0	0.0	0.0	4.0	99	0.88	21.8
21	Selcal Control Panel	Digital Computer	72.384	2.0	0.0	0.0	2.0	145	0.44	31.9
22	Passenger Address Amplifier 1	High-power/high-frequency components	139.992	4.0	0.0	0.0	8.0	1,120	1.76	246.9
23	Passenger Address Amplifier 2	High-power/high-frequency components	139.992	4.0	0.0	0.0	8.0	1,120	1.76	246.9
24	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.76	79.9
25	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.76	79.9
26	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	8.0	363	1.76	79.9
27	PA Speaker	High-power/high-frequency components	45.320	4.0	0.0	0.0	6.0	272	1.32	59.9
28	Cockpit Voice Recorder Control Panel	Digital Computer	26.000	2.0	0.0	0.0	2.0	52	0.44	11.5
29	Cockpit Voice Recorder	Digital	150.000	3.0	0.0	0.0	3.0	450	0.66	99.2
	TOTAL (Σ)		2,765					12,541		2,765

MTTR Requirement (hour) 1.00

$M_{system} = \dfrac{\Sigma \lambda M_i}{\lambda} = \dfrac{12{,}541}{2{,}765} = \boxed{4.54}$

$(Rpj = (MTTR/M_{system})Mi = R_{pj} = \dfrac{MTTR}{M_{system}} = \dfrac{1.00}{4.54} = \boxed{0.2205}$

Therefore: Allocated Active Repair Time (R_{pj}) = $\boxed{0.2205} \times M_i$

To check MTTR REQUIREMENT (HOUR) $\dfrac{\Sigma \lambda R_{pj}}{\Sigma \lambda} = \dfrac{2{,}765}{2{,}765} = \boxed{1.00}$ **PASSED**

Table I-11 Validation results by using LINEAR formula for new score values

No	System / Sub System	Generic Module Types	λ	SCORE			ΣKj	Σ	Allocated	Σ
			10^{-6} hour	Kj 1	Kj 2	Kj 3		λKj	R_{pj} (hour)	λR_{pj}
1	Audio Selector Panel 1	High-level analogue	166.805	3.0	0.0	0.0	6.0	1,001	1.47	245.2
2	Audio Selector Panel 2	High-level analogue	166.805	3.0	0.0	0.0	5.0	834	1.22	204.3
3	Headset 1	Communication	156.400	2.0	0.0	0.0	4.0	626	0.98	153.3
4	Headset 2	Communication	156.400	2.0	0.0	0.0	4.0	626	0.98	153.3
5	Handheld Microphone 1	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.98	348.5
6	Handheld Microphone 2	Communication	355.700	2.0	0.0	0.0	4.0	1,423	0.98	348.5
7	Speaker 1	Communication	47.460	2.0	0.0	0.0	4.0	190	0.98	46.5
8	Speaker 2	Communication	47.460	2.0	0.0	0.0	5.0	237	1.22	58.1
9	VHF 1 Antenna	High-power/high-frequency components	10.758	3.0	0.0	0.0	3.0	32	0.73	7.9
10	VHF 1 Transceiver	High-power/high-frequency components	60.000	3.0	0.0	0.0	3.0	180	0.73	44.1
11	VHF 1 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.49	52.2
12	VHF 2 Antenna	High-power/high-frequency components	10.758	3.0	0.0	0.0	3.0	32	0.73	7.9
13	VHF 2 Transceiver	High-power/high-frequency components	60.000	3.0	0.0	0.0	3.0	180	0.73	44.1
14	VHF 2 Control Panel	Digital Computer	106.596	2.0	0.0	0.0	2.0	213	0.49	52.2
15	HF Antenna	High-power/high-frequency components	33.100	3.0	0.0	0.0	3.0	99	0.73	24.3
16	HF Lightning Arrestor	Lights	23.814	2.0	0.0	0.0	2.0	48	0.49	11.7
17	HF Antenna Coupler	High-power/high-frequency components	96.089	3.0	0.0	0.0	3.0	288	0.73	70.6
18	HF Transceiver	High-power/high-frequency components	58.338	3.0	0.0	0.0	3.0	175	0.73	42.9
19	HF Control Panel	Digital Computer	11.775	2.0	0.0	0.0	2.0	24	0.49	5.8
20	Selcal Decoder	High-power/high-frequency components	24.675	3.0	0.0	0.0	3.0	74	0.73	18.1
21	Selcal Control Panel	Digital Computer	72.384	2.0	0.0	0.0	2.0	145	0.49	35.5
22	Passenger Address Amplifier 1	High-power/high-frequency components	139.992	3.0	0.0	0.0	6.0	840	1.47	205.8
23	Passenger Address Amplifier 2	High-power/high-frequency components	139.992	3.0	0.0	0.0	6.0	840	1.47	205.8
24	PA Speaker	High-power/high-frequency components	45.320	3.0	0.0	0.0	6.0	272	1.47	66.6
25	PA Speaker	High-power/high-frequency components	45.320	3.0	0.0	0.0	6.0	272	1.47	66.6
26	PA Speaker	High-power/high-frequency components	45.320	3.0	0.0	0.0	6.0	272	1.47	66.6
27	PA Speaker	High-power/high-frequency components	45.320	3.0	0.0	0.0	5.0	227	1.22	55.5
28	Cockpit Voice Recorder Control Panel	Digital Computer	26.000	2.0	0.0	0.0	2.0	52	0.49	12.7
29	Cockpit Voice Recorder	Digital	150.000	3.0	0.0	0.0	3.0	450	0.73	110.2
	TOTAL (Σ)		2,765					11,287		2,765

MTTR Requirement (hour) 1.00

$M_{system} = \frac{\Sigma \lambda M_i}{\lambda} = \frac{11{,}287}{2{,}765} = \boxed{4.08}$

$(Rpj = (MTTR/M_{system})Mi = R_{pj} = \frac{MTTR}{M_{system}} = \frac{1.00}{4.08} = \boxed{0.2450}$

Therefore: Allocated Active Repair Time (R_{pj}) = $\boxed{0.2450}$ x M_i

To check MTTR REQUIREMENT (HOUR) $\frac{\Sigma \lambda R_{pj}}{\Sigma \lambda} = \frac{2{,}765}{2{,}765} = \boxed{1.00}$ **PASSED**

able I-12 Validation results summary for Aircraft Communication Systems

No	Components	Generic Module Types	Allocation Value (Hour)			ERROR	
			Existing	**LOG**	**LINEAR**	**LOG**	**LINEAR**
1	Audio Selector Panel 1	High-level analogue	0.72	1.32	1.47	0.60	0.75
2	Audio Selector Panel 2	High-level analogue	0.84	1.10	1.22	0.26	0.38
3	Headset 1	Communication	0.96	0.88	0.98	-0.08	0.02
4	Headset 2	Communication	0.96	0.88	0.98	-0.08	0.02
5	Handheld Microphone 1	Communication	0.96	0.88	0.98	-0.08	0.02
6	Handheld Microphone 2	Communication	0.96	0.88	0.98	-0.08	0.02
7	Speaker 1	Communication	0.96	0.88	0.98	-0.08	0.02
8	Speaker 2	Communication	1.44	1.32	1.22	-0.12	-0.22
9	VHF 1 Antenna	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
10	VHF 1 Transceiver	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
11	VHF 1 Control Panel	Digital Computer	0.48	0.44	0.49	-0.04	0.01
12	VHF 2 Antenna	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
13	VHF 2 Transceiver	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
14	VHF 2 Control Panel	Digital Computer	0.48	0.44	0.49	-0.04	0.01
15	HF Antenna	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
16	HF Lightning Arrestor	Lights	0.24	0.22	0.49	-0.02	0.25
17	HF Antenna Coupler	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
18	HF Transceiver	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
19	HF Control Panel	Digital Computer	0.48	0.44	0.49	-0.04	0.01
20	Selcal Decoder	High-power/high-frequency components	0.96	0.88	0.73	-0.08	-0.23
21	Selcal Control Panel	Digital Computer	0.48	0.44	0.49	-0.04	0.01
22	Passenger Address Amplifier 1	High-power/high-frequency components	1.92	1.76	1.47	-0.16	-0.46
23	Passenger Address Amplifier 2	High-power/high-frequency components	1.92	1.76	1.47	-0.16	-0.46
24	PA Speaker	High-power/high-frequency components	1.92	1.76	1.47	-0.16	-0.46
25	PA Speaker	High-power/high-frequency components	1.92	1.76	1.47	-0.16	-0.46
26	PA Speaker	High-power/high-frequency components	1.92	1.76	1.47	-0.16	-0.46
27	PA Speaker	High-power/high-frequency components	1.44	1.32	1.22	-0.12	-0.22
28	Cockpit Voice Recorder Control Panel	Digital Computer	0.48	0.44	0.49	-0.04	0.01
29	Cockpit Voice Recorder	Digital	0.24	0.66	0.73	0.42	0.49
					QTY	28	28
					%	96.55%	96.55%
					AVERAGE	-0.04	-0.09

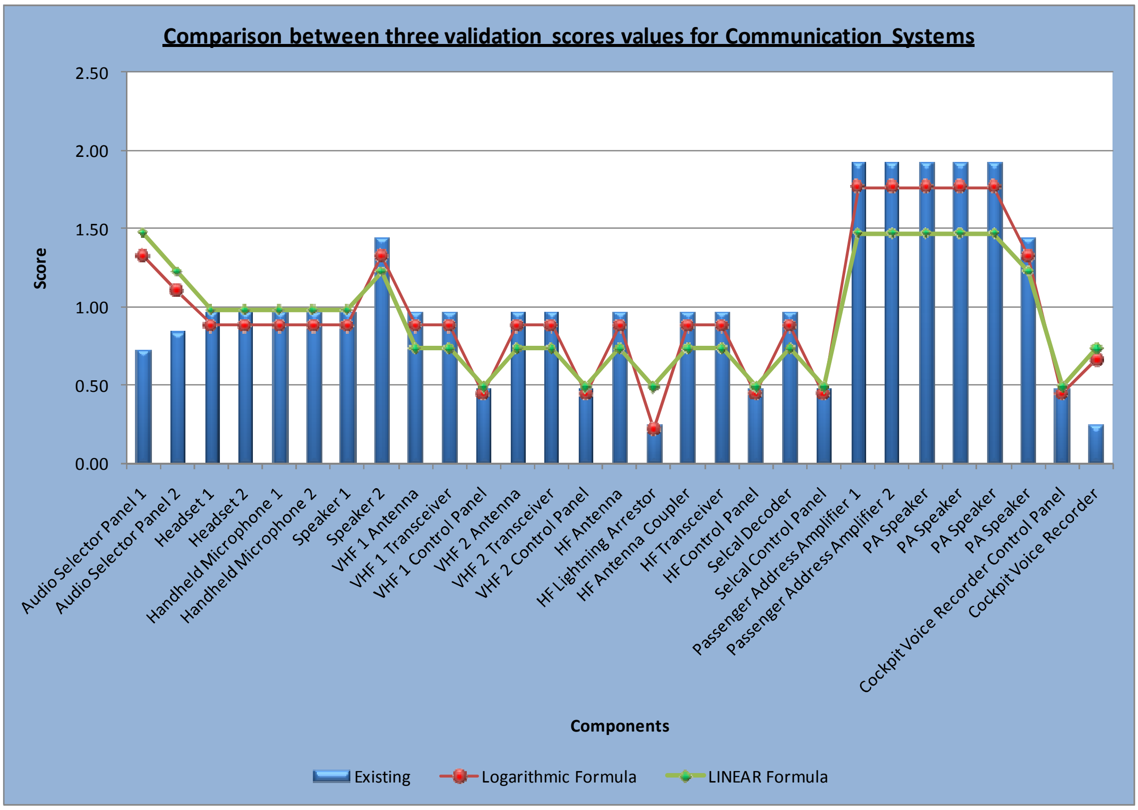

Figure I-5 Comparison between all validation results for maintainability allocation

Appendix J Validation – BAe 146: Maintainability allocation

J.1 Maintainability allocation – Approach 1

Table J-1 The maintainability allocation tasks time for BAe 146 – 300 by using estimation MTTR equal to 1.00 hour – Allocation approach 1

No	System / Sub System	Generic Module Types (in accordance with New Allocation Scheme)	Kj 1	Kj 2	Kj 3	ΣKj	λ x 10^{-6}	$\lambda j Kj$	Allocated Rpj (hour)	$\lambda * Rpj$
1	ACTUATOR	Electromechanical Equipment	3.0	2.0	4.0	9.0	136.8370	1231.53	0.85	115.79
2	ANTI SKID	Electromechanical Equipment	3.0	2.0	4.0	9.0	672.3670	6051.30	0.85	568.94
3	BRAKE	Mechanial Structure with mechanisms	8.0	2.0	4.0	14.0	636.0930	8905.30	1.32	837.27
4	BRAKE ASSY	Electromechanical Equipment + Mechanial Structure with mechanism	5.5	2.0	4.0	11.5	2.1000	24.15	1.08	2.27
5	CONNECTOR	Interconnections (Mechanical)	3.0	2.0	4.0	9.0	41.0560	369.50	0.85	34.74
6	CONTROL UNIT	Power Supplies + Electromechanical Equipment + Digital	2.0	2.0	4.0	8.0	235.5158	1884.13	0.75	177.14
7	HYDRAULIC	Electromechanical Equipment + Interconnections (Mechanical)	3.0	2.0	4.0	9.0	598.1837	5383.65	0.85	506.17
8	PROXIMITY SENSOR	High-power/high-frequency components	4.0	4.0	4.0	12.0	672.3670	8068.40	1.13	758.59
9	PROXIMITY SWITCH	High-power/high-frequency components	4.0	4.0	4.0	12.0	116.2524	1395.03	1.13	131.16
10	SELECTOR VALVE	Interconnections (Mechanical) + Electromechanical equipment	3.0	2.0	4.0	9.0	95.2380	857.14	0.85	80.59
11	SENSOR	High-power/high-frequency components	4.0	4.0	2.0	10.0	6.9634	69.63	0.94	6.55
12	STEERING	Mechanical Structures	6.0	2.0	4.0	12.0	3.2361	38.83	1.13	3.65
13	STRUCTURE	Mechanical Structures	6.0	2.0	4.0	12.0	1.0000	12.00	1.13	1.13
14	STRUT	Mechanical Structures	6.0	2.0	4.0	12.0	6.6270	79.52	1.13	7.48
15	SWITCH	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	116.2524	1046.27	0.85	98.37
16	TIRE	Mechanial Structures	6.0	2.0	4.0	12.0	14.9601	179.52	1.13	16.88
17	UPLOCK SWITCH	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	67.0166	603.15	0.85	56.71
18	V-BELT	Mechanical Structures	6.0	2.0	4.0	12.0	164.0140	1968.17	1.13	185.05
19	WARNING LIGHT	Light	1.0	4.0	4.0	9.0	32.4918	292.43	0.85	27.49
20	WARNING SYSTEM	High-power/high-frequency components	4.0	4.0	4.0	12.0	20.4420	245.30	1.13	23.06
21	WHEEL	Mechanial Structures	6.0	2.0	4.0	12.0	3.2361	38.83	1.13	3.65
22	WIRE	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	0.5090	4.58	0.85	0.43
23	WIRE HARNESS	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	2.2727	20.45	0.85	1.92
									Average	
						241.50	3,645.03	38,768.85	0.99	3,645.03

MTTR	1.00	Estimation
$K = \Sigma Fj Kj / \Sigma FR$	10.64	
$Rpj = (MTTR/K)*Kj$	0.0940	
Check: MTTRsystem	1.00	GOOD

Notes: Kj2 = Same value as BITE from Check list A
Kj3 = Average question 1, 2, 3, & 4 from Check list A,

Table J-2 The summary of maintainability allocation and prediction tasks time for BAe 146 – 300 – Allocation approach 1

No	Components	Maintenance Allocation Time MTTR = 1.00 hour
1	ACTUATOR	0.85
2	ANTI SKID	0.85
3	BRAKE	1.32
4	BRAKE ASSY	1.08
5	CONNECTOR	0.85
6	CONTROL UNIT	0.75
7	HYDRAULIC	0.85
8	PROXIMITY SENSOR	1.13
9	PROXIMITY SWITCH	1.13
10	SELECTOR VALVE	0.85
11	SENSOR	0.94
12	STEERING	1.13
13	STRUCTURE	1.13
14	STRUT	1.13
15	SWITCH	0.85
16	TIRE	1.13
17	UPLOCK SWITCH	0.85
18	V-BELT	1.13
19	WARNING LIGHT	0.85
20	WARNING SYSTEM	1.13
21	WHEEL	1.13
22	WIRE	0.85
23	WIRE HARNESS	0.85

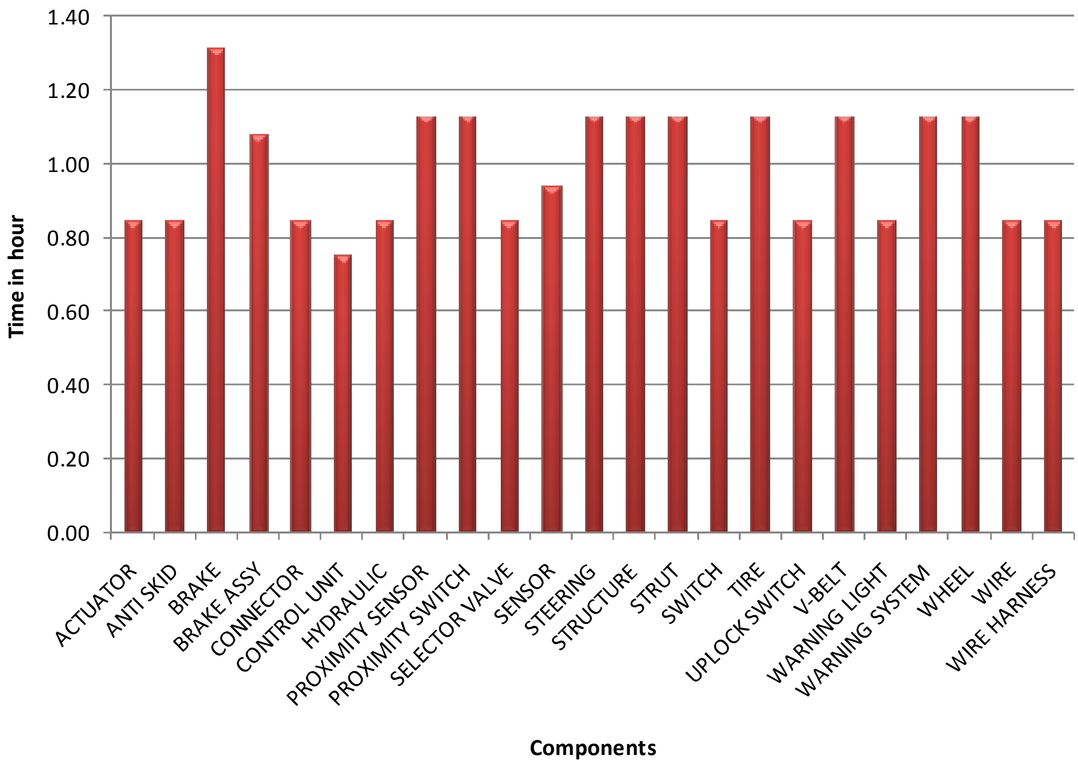

Figure J-1 The trend of maintainability allocation and prediction tasks time for BAe 146 – 300 – Allocation approach 1

J.2 Maintainability allocation – Approach 2

Table J-3 The maintainability allocation tasks time for BAe 146 – 300 by using average MTTR equal to 0.53 hour – Allocation approach 2

No	System / Sub System	Generic Module Types (in accordance with New Allocation Scheme)	K_j 1	K_j 2	K_j 3	ΣK_j	λ $\times 10^{-6}$	$\lambda_j K_j$	Allocated R_{pj} (hour)	$\lambda * R_{pj}$
1	ACTUATOR	Electromechanical Equipment	3.0	2.0	4.0	9.0	136.8370	1231.53	0.45	61.37
2	ANTI SKID	Electromechanical Equipment	3.0	2.0	4.0	9.0	672.3670	6051.30	0.45	301.54
3	BRAKE	Mechanial Structure with mechanisms	8.0	2.0	4.0	14.0	636.0930	8905.30	0.70	443.75
4	BRAKE ASSY	Electromechanical Equipment + Mechanial Structure with mechanism	5.5	2.0	4.0	11.5	2.1000	24.15	0.57	1.20
5	CONNECTOR	Interconnections (Mechanical)	3.0	2.0	4.0	9.0	41.0560	369.50	0.45	18.41
6	CONTROL UNIT	Power Supplies + Electromechanical Equipment + Digital	2.0	2.0	4.0	8.0	235.5158	1884.13	0.40	93.89
7	HYDRAULIC	Electromechanical Equipment + Interconnections (Mechanical)	3.0	2.0	4.0	9.0	598.1837	5383.65	0.45	268.27
8	PROXIMITY SENSOR	High-power/high-frequency components	4.0	4.0	4.0	12.0	672.3670	8068.40	0.60	402.05
9	PROXIMITY SWITCH	High-power/high-frequency components	4.0	4.0	4.0	12.0	116.2524	1395.03	0.60	69.51
10	SELECTOR VALVE	Interconnections (Mechanical) + Electromechanical equipment	3.0	2.0	4.0	9.0	95.2380	857.14	0.45	42.71
11	SENSOR	High-power/high-frequency components	4.0	4.0	2.0	10.0	6.9634	69.63	0.50	3.47
12	STEERING	Mechanical Structures	6.0	2.0	4.0	12.0	3.2361	38.83	0.60	1.94
13	STRUCTURE	Mechanical Structures	6.0	2.0	4.0	12.0	1.0000	12.00	0.60	0.60
14	STRUT	Mechanical Structures	6.0	2.0	4.0	12.0	6.6270	79.52	0.60	3.96
15	SWITCH	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	116.2524	1046.27	0.45	52.14
16	TIRE	Mechanial Structures	6.0	2.0	4.0	12.0	14.9601	179.52	0.60	8.95
17	UPLOCK SWITCH	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	67.0166	603.15	0.45	30.06
18	V-BELT	Mechanical Structures	6.0	2.0	4.0	12.0	164.0140	1968.17	0.60	98.07
19	WARNING LIGHT	Light	1.0	4.0	4.0	9.0	32.4918	292.43	0.45	14.57
20	WARNING SYSTEM	High-power/high-frequency components	4.0	4.0	4.0	12.0	20.4420	245.30	0.60	12.22
21	WHEEL	Mechanial Structures	6.0	2.0	4.0	12.0	3.2361	38.83	0.60	1.94
22	WIRE	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	0.5090	4.58	0.45	0.23
23	WIRE HARNESS	Power Supplies + Interconnection (Electrical)	3.0	2.0	4.0	9.0	2.2727	20.45	0.45	1.02
									Average	
						241.50	3,645.03	38,768.85	0.52	1,931.87

MTTR	0.53	Average tasks time from MIL-HDBK-472, Procedure III
$K = \Sigma F_j K_j / \Sigma FR$	10.64	
$R_{pj} = (MTTR/K) * K_j$	0.0498	
Check: MTTRsystem	0.53	GOOD

Notes: Kj2 = Same value as BITE from Check list A
Kj3 = Average question 1, 2, 3, & 4 from Check list A,

Table J-4 The summary of maintainability allocation and prediction tasks time for BAe 146 – 300 – Allocation approach 2

No	Components	Maintenance Allocation Time MTTR = 0.53 hour
1	ACTUATOR	0.45
2	ANTI SKID	0.45
3	BRAKE	0.70
4	BRAKE ASSY	0.57
5	CONNECTOR	0.45
6	CONTROL UNIT	0.40
7	HYDRAULIC	0.45
8	PROXIMITY SENSOR	0.60
9	PROXIMITY SWITCH	0.60
10	SELECTOR VALVE	0.45
11	SENSOR	0.50
12	STEERING	0.60
13	STRUCTURE	0.60
14	STRUT	0.60
15	SWITCH	0.45
16	TIRE	0.60
17	UPLOCK SWITCH	0.45
18	V-BELT	0.60
19	WARNING LIGHT	0.45
20	WARNING SYSTEM	0.60
21	WHEEL	0.60
22	WIRE	0.45
23	WIRE HARNESS	0.45

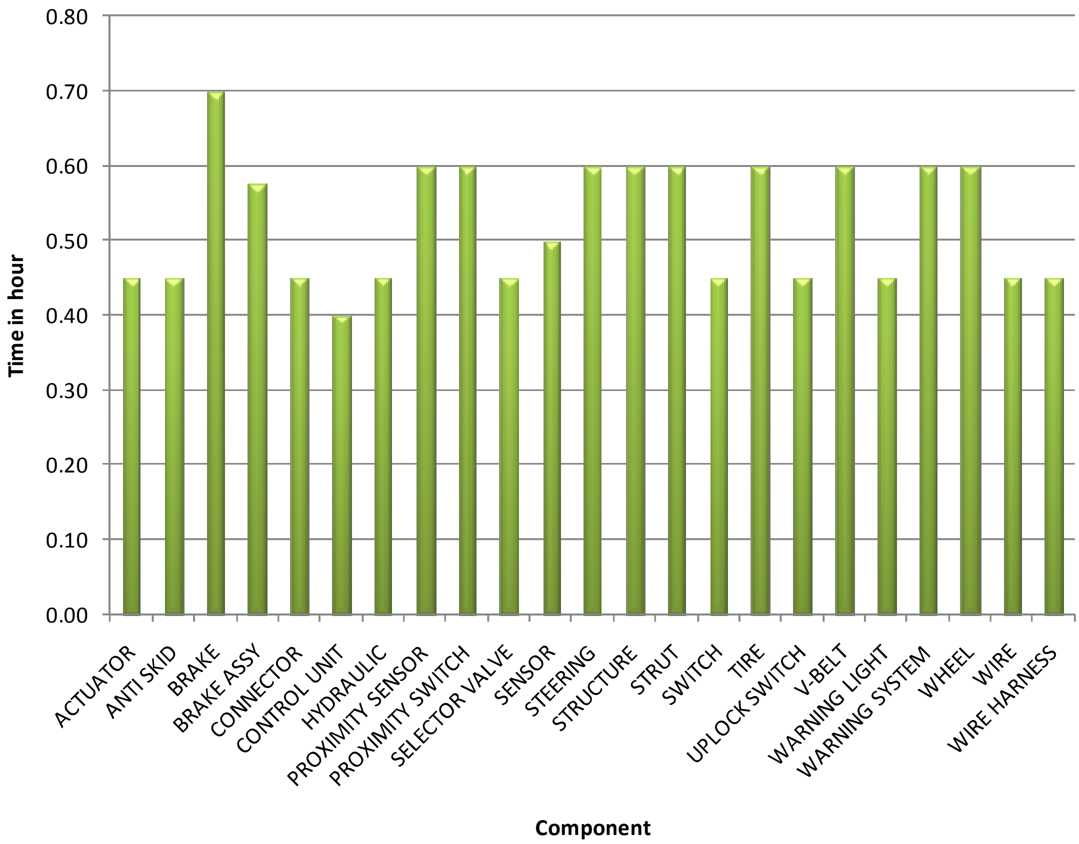

Figure J-2 The trend of maintainability prediction and allocation times for both MTT values for BAe 146 – 300 Landing Gear – Allocation approach 2

Appendix K Validation – Jetstream 31: Maintainability allocation

K.1 Maintainability allocation – Approach 1

Table K-1 Maintainability prediction tasks time prediction for Jetstream 31 – Landing Gear – Approach 1

No	Components	List of Modules	Allocation (Kj)			Σ Kj	λ	λj Kj	Allocated Rpj	λRpj
			Module	Isolation	Accessiblity		Fail/Cycles 106		(hour)	
1	Main Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.29885	16.09	0.51	1.16
2	Main Landing Gear Radius Rod	Electromechanical Equipment + Interconnection (Mechanical)	3	4	3	10	7.99420	79.94	0.72	5.77
3	Main Landing Gear	Mechanical Structure with mechanism	8	4	2	14	249.74050	3,496.37	1.01	252.37
4	Nose Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.29885	16.09	0.51	1.16
5	Nose Landing Gear	Mechanical Structure with mechanism	8	4	2	14	177.91695	2,490.84	1.01	179.79
							440.24935	6,099.33		440.25

MTTR	1.00	Estimation
K = Σλj Kj / ΣFR	13.85	
Rpj = (MTTR/K)*Kj	0.0722	
Check: MTTRsystem	1.00	GOOD

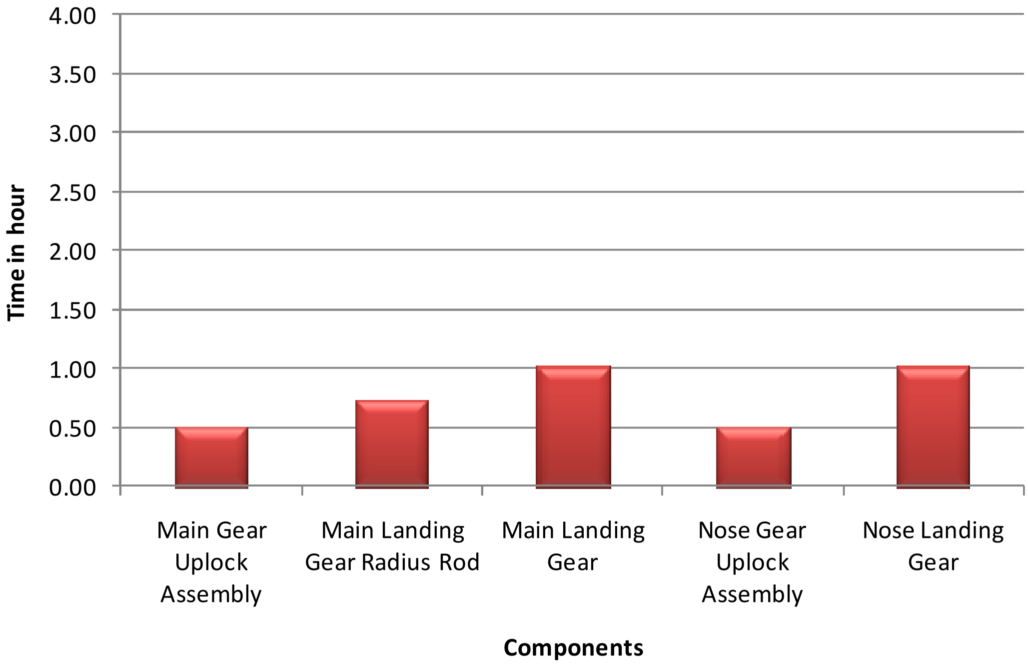

Figure K-1 The trend of maintainability prediction and allocation times for both MTT values for Jetstream 31 Landing Gear – Approach 1

K.2 Maintainability allocation – Approach 2

Table K-2 Maintainability prediction tasks time prediction for Jetstream 31 – Landing Gear – Approach 2

No	Components	List of Modules	Allocation (Kj)			Σ Kj	λ	λj Kj	Allocated Rpj	λRpj
			Module	Isolation	Accessiblity		Fail/Cycles 106		(hour)	
1	Main Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.29885	16.09	1.90	4.37
2	Main Landing Gear Radius Rod	Electromechanical Equipment + Interconnection (Mechanical)	3	4	3	10	7.99420	79.94	2.71	21.70
3	Main Landing Gear	Mechanical Structure with mechanism	8	4	2	14	249.74050	3,496.37	3.80	948.90
4	Nose Gear Uplock Assembly	Electromechanical Equipment + Interconnection (Mechanical)	3	2	2	7	2.29885	16.09	1.90	4.37
5	Nose Landing Gear	Mechanical Structure with mechanism	8	4	2	14	177.91695	2,490.84	3.80	676.00
							440.24935	6,099.33		1,655.34

MTTR	3.76	Estimation
K = Σλj Kj / ΣFR	13.85	
Rpj = (MTTR/K)*Kj	0.2714	
Check: MTTRsystem	3.76	GOOD

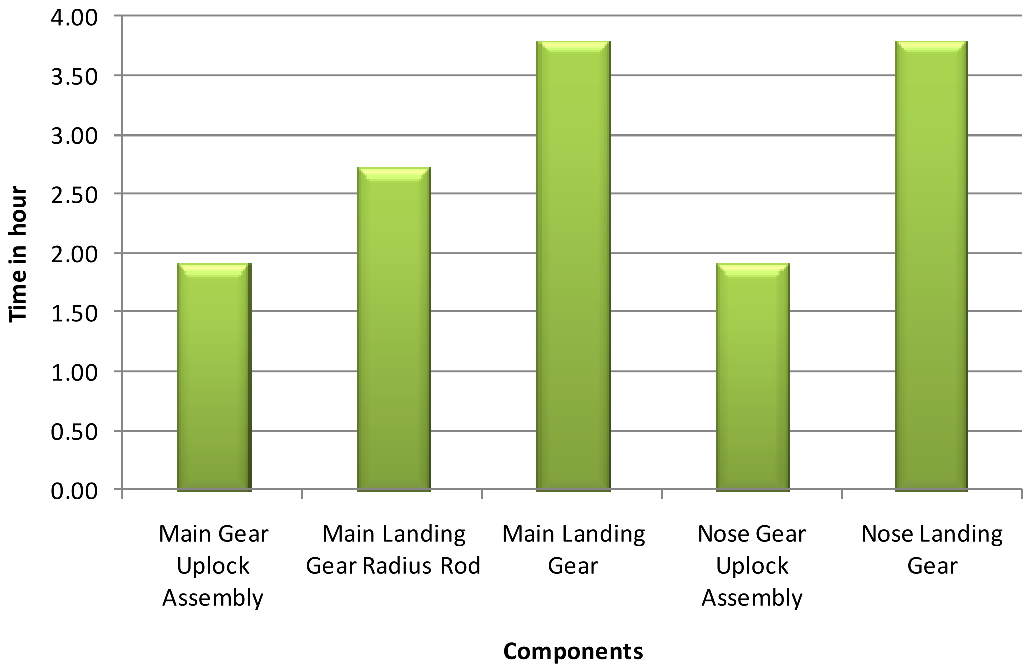

Figure K-2 The trend of maintainability prediction and allocation times for both MTT values for Jetstream 31 Landing Gear – Approach 2

Appendix L Jetstream – Maintenance Analysis

Aircraft : **Jetstream 31**
Component Name : **Main Gear Uplock**

Step	Maintenance	Scoring Comments
Removal procedure		
1	De-energise aircraft DC bus-bars	Manpower = 1 person Tools = None
2	Raise aircraft on jacks	Manpower = 3 person minimum Tools = Aircraft jacks and jigs and fixtures
3	Reduce system pressure to zero by release valve	Manpower = 1 person Tools = Standard tools
4	Disconnect pipes from uplock jack and install blanking cap	
5	Remove nuts, washers, and bolts from microswitch	
6	Identify cable for subsequent connection	
7	Remove split pins, nut, washer, bolts securing uplock unit	
8	Remove uplock unit from aircraft	
Prior Installation		
9	Disconnect and remove unions from normal-down emergency-down and up connection on removed uplock jack	Manpower = 1 person Tools = Standard tools
10	Remove blanking cap from replacement uplock jack	
11	Install new fibre seals and O-ring seals install unions in normal-down emergency-down and up connections	
Installation procedure		
12	Position and secure uplock unit on mounting bracket	
13	Install microswitch (mechanical and electrical connection)	
14	Connect hydraulic pipes	
15	Energise aircraft DC Bus	
16	Tighten connection and install nose landing gear downlock	Manpower = 2 person Tools = Standard Tools Safety = High
17	Operate emergency hand pump and tighten connection	Manpower = 2 person Tools = Standard Tools

		Safety = High
18	Remove LG ground lock and operate emergency hydraulic hand pump until leg is up and locked	Manpower = 2 person Tools = Hydraulic Pump Safety = High
19	Check clearance between uplock and hook	Manpower = 2 person Tools = Filler gauge Safety = High
20	Reset release valve	Manpower = 1 person Tools = Standard tools
22	Perform functional test	Manpower = 2 person minimum Tools = Special functional test
23	Lower aircraft	Manpower = 3 person minimum Tools = None Caution level = High

Aircraft : **Jetstream 31**
Component Name : **Radius Rod Change**

Step	Maintenance	Scoring Comments
Removal procedure		
1	Jack the aircraft at the Nose and Wing Station	Manpower = 2 person minimum Tools -= 3 aircraft jacks and jigs and fixtures Caution level = High
2	Reduce hydraulic system pressure to zero by release valve	Manpower = 2 person minimum Tools = Standard tools
3	Open, tag, and safety circuit breaker	Electronics components Manpower -= 1 person Tools = None
4	De-energise aircraft DC Bus-bars	
5	Disconnect electrical cable from down lock microswitch	
6	Remove clips securing cable from unit cylinder	Manpower = 1 person Tools = Standard Tools
7	Disconnect flexible hoses from radius rod	
8	Install blanking cap to hose ends	
9	Remove radius rod from aircraft	
Prior Installation		
10	Remove banjo bolt and shuttle valve	Manpower = 1 person Tools =Standard Tools
11	Install O-Ring to banjo bolt and shuttle vale	
12	Install shuttle valve parallel to radius rod	
13	Secure shuttle valve with banjo bolt	
14	Safety banjo bolt with lockwire	
15	Lubricate O-ring seals with hydraulic oil	
16	Remove blanking caps	
17	Install O-ring seal restrictor and install securely and safety with lockwire	
18	Make sure replacement unit is fully extended and locked	
Installation procedure		
19	Install radius rod anchorage end	Manpower = 1 person Tools = None
20	Position unit ram end connection on leg attachment, DO NOT SECURE	
21	Check alignment	Manpower = 1 person Tools = Clinometers
22	Secure radius rod and lock with split pin	Manpower = 1 person Tools = Standard tool
23	Safety radius rod ram end adjuster with lockwire	Manpower = 1 person Tools = Standard tools and wire twister

24	Check clearance at anchorage end connection	Manpower = 1 person Tools = filler gauge & standard tools
25	Torque loaded to 500 $\pm$ 50 lbf in	Manpower = 1 person Tools = Torque wrench
26	Safety nut to key with stainless steel lockwire	Manpower = 1 person Tools = Standard tools & wire twister
27	Connect flexible hoses	Manpower = 1 person Tools = Standard wrenches
28	Bleed main landing gear	Manpower = 1 person Tools = Standards tools
29	Adjust main landing gear	Manpower = 2 person minimum Tools = Special functional test
30	Perform functional test	
31	Lower aircraft	Manpower = 3 person minimum Tools = None Caution level = High

Aircraft	:	**Jetstream 31**
Component Name	:	**Main Gear Leg**

Step	Maintenance	Scoring Comments
	Removal procedure	
1	Jack the aircraft	Manpower = 3 person Tools = Jacking equipments Safety = High
2	Release hydraulic pressure in main and brake system	Manpower = 2 person Tools = Standard tools
3	Disconnect lockwire and remove door link nut and door link angled washer, securing landing gear bay door operating rod	Manpower = 1 person Tools = Standard tools
4	Disconnect & remove anti skid	
5	Disconnect & remove brake unit	
6	Disconnect brake system flexible hoses	
7	Disconnect radius rod from leg and secure to landing gear bay roof	
8	Disconnect & remove yoke bearing half caps. Ease leg from bearing housing and carefully remove from landing gear bay	
	Installation procedure (New leg)	
1	Open gas charging valve and slowly release pressure	Manpower = 1 person Tools = Standard Tools
2	Remove free and datum bearing.	
3	Clean & examine for condition and wear	Manpower = 1 person Tools = White Sprit
4	Disconnect rigid brake pipes from distribution block and install blanking cap	Manpower = 1 person Tools = Standard Tools
5	Disconnect rigid brakes pipes mounting bracket from leg yoke	
6	Disconnect flexible hoses from axle bracket and distribution block	
7	Disconnect and remove six unions complete with O-ring	
	Prior Installation	
1	Make sure toggle assembly shims are in correct position	Manpower = 1 person Tools = Standard Tools
2	Make sure toggle assembly shims in correct position for toe-in	
3	Clean & examine pipes and brackets for signs of damage and/or wear	

4	Examine new leg for obvious damage	
5	Remove blanking caps from distribution block and install six unions complete with new O-ring seals. Tighten unions	
6	Remove blanking caps from axle bracket and hoses. Connect and secure flexible hoses	
7	Place rigid pipe assembly against leg and connect mounting bracket to yoke.	
8	Remove blanking caps and connect and secure lower ends of pipes to distribution block.	
9	Clean protective treatment from yoke bearing spigots and apply specified grease	
10	Install datum split bearing to front spigot	
11	Make sure wide flanges face leg yoke, slide free bearing onto rear spigot	
Installation Main Landing leg assembly		
1	Make sure toggles on leg face forward. Move leg into landing gear bay and align yoke bearing spigots with their associated housings	Manpower = 2 person Tools = Standard tools
2	Make sure free bearing on rear spigot has wide flanges facing forwards, towards landing gear yoke	
3	Position bearing half caps on their respective bearings. Rotate each bearing, aligning scallops with locating pins	
4	Push yoke fully home. Install four bolt and barrel nuts, Torques bolts to 335 to 355 lbf in. Safety with lockwire and make sure barrel nuts are positioned correctly	Manpower = 1 person Tools = Standard tools & Torque wrench
5	Install radius rod	Manpower = 2 person Tools = Clinometers, Standard tools
6	Connect all flexible hoses	Manpower = 1 person Tools = Standard tools
7	Install brake unit	
8	Install anti skid unit	
9	Release gas pressure and replenish main gear oleo leg	
10	Bleed and test brakes	
11	Perform adjustment & test procedure	
12	Lowered off jacks	Manpower = 3 person Tools = Jacking equipment Safety = High

Aircraft : **JETSTREAM 31**
Component Name : **Nose Gear Leg**

Step	Maintenance	Scoring Comments
Removal procedure		
1	Raise aircraft on jacks	Manpower = 3 persons Tools = Jacking equipments Safety = High
2	Release hydraulic pressure	Manpower = 1 person Tools = Standard tools
3	Lower access panels	
4	Disconnect, open, & restrain forwards nose LG doors	
5	Disconnect rear door operating rid from NLG leg	
6	De-energise aircraft DC bus-bars	
7	Open & tag essential bus-bar circuit breakers	
8	Place a warning notice on circuit breaker	
9	Switch OFF the taxi lamp switch on roof panel	
10	Disconnect oleo switch from mounting bracket, leaving upper but undisturbed	
11	Release switch loom conduit from leg and secure conduit	
12	Remove nose wheels, install cones and axle nuts and secure wheel locking plates	
13	Disconnect steering follow-up mechanism links arc enter bolt, tie back upper link	
14	Energise aircraft DC Bus bars	
15	Remove tag and close essential bus-bar circuit breaker GEAR CONT/WARN and GEAR POSN IND	
16	Set LG selector know UP and operate hand pump sufficiently to disengage downlock pin from hook	
17	Release hydraulic pressure	
18	De-energise aircraft DC bus bar	
19	Open & tag essential bus bar circuit breaker	
20	Open bleed screws on steering jack to disperse residual fluid, then disconnect flexible hose from rear face of leg yoke	
21	Disconnect retraction jack from leg	
22	Support leg, restrain leg yoke, then disconnect and remove yoke bearing half caps.	
23	Ease leg from bearing housing then carefully remove from wheel bay	Manpower = 2 person Tools = Standard tools Safety = High

<table>
<tr><th colspan="3">Installation procedure (New Leg)</th></tr>
<tr><td>1</td><td>Open charging valve, release pressure</td><td>Manpower = 1 person;
Tools = Standard tools</td></tr>
<tr><td>2</td><td>Remove free bearing and split bearing from leg & half bearing from aircraft. Clean in solvent (white spirit) and examine for condition and wear</td><td>Manpower = 1 person
Tools = White spirit, standard tools
Safety = medium</td></tr>
<tr><td>3</td><td>Disconnect door break rod connection</td><td rowspan="5">Manpower = 2 person;
Tools = Standard tools</td></tr>
<tr><td>4</td><td>Disconnect and remove steering hoses</td></tr>
<tr><td>5</td><td>Disconnect and remove bulkhead union from right yoke web</td></tr>
<tr><td>6</td><td>Disconnect and remove unions from steering jack, discard O-ring seals</td></tr>
<tr><td>7</td><td>Remove follow-up mechanism upper link from aircraft</td></tr>
<tr><th colspan="3">Prior Installation</th></tr>
<tr><td>1</td><td>Disconnect and remove upper toggle link; assemble to steering selector in same direction as removed link</td><td rowspan="6">Manpower = 1 person
Tools = Standard tools</td></tr>
<tr><td>2</td><td>Install door operating rod to replacement leg, safety with split pin</td></tr>
<tr><td>3</td><td>Install bulkhead unions to right yoke web</td></tr>
<tr><td>4</td><td>Install unions, complete with new O-ring seals into steering jack connections</td></tr>
<tr><td>5</td><td>Remove caps, connect and tighten steering unions</td></tr>
<tr><td>6</td><td>Attach bolt and secure with lock wire</td></tr>
<tr><th colspan="3">Installation procedure</th></tr>
<tr><td>1</td><td>Clean inhibitor from yoke bearing spigots and coat with specified grease. Make sure wide flange inboard and install free bearing to right spigot</td><td>Manpower = 1 person
Tools = Standard tools and grease</td></tr>
<tr><td>2</td><td>Secure yoke bearing with lockwire</td><td></td></tr>
<tr><td>3</td><td>Lubricate the bearing using specified grease. Install ½ to left housing on aircraft and remaining half to left half cap, making sure scallop in each wide flange faces inboard to engage with its associated barrel nuts</td><td>Manpower = 1 person
Tools = Standard tools and grease</td></tr>
<tr><td>4</td><td>Transfer electrical loom conduit securing clips</td><td rowspan="2">Manpower = 1 person
Tools = Standard tools</td></tr>
<tr><td>5</td><td>With leg torque links facing forward, move leg into nose wheel bay and raise until yoke bearings are engaged and seated in their respective housings</td></tr>
<tr><td>6</td><td>Install half caps and attachment bolts and torque to 200 to 250 lbf.in</td><td>Manpower = 1 person
Tools = Standard tools and Torque</td></tr>
</table>

		wrench
7	Connect retraction jack to leg. Identify original or new installation	Manpower = 1 person Tools = Standard tools
8	Remove caps, connect and secure steering hoses	
9	Connect steering follow-up links. Make sure gap of 0.001 to 0.002 exists between links before installing split pin	Manpower = 1 person Tools = Standard tools & filler gauge
10	Install taxi lamp	Manpower = 1 person Tools = Standard tools
11	Install nose oleo switch	
12	Remove tag and close essential bus-bar circuit breaker	
13	Install left and right wheel	
14	Replenish nose oleo	
15	Adjust nose landing gear	
16	Cleaning work area and clear all tools	
17	Close access panel	
18	Perform functional test	
19	Lowered the aircraft	